AMATEUR TELESCOPE MAKING

SCIENTIFIC AMERICAN PUBLISHING CO.

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SCIENTIFIC AMERICAN PUBLISHING CO.
1928

Printed in the
United States of America
by ANDREW H. KELLOGG CO.

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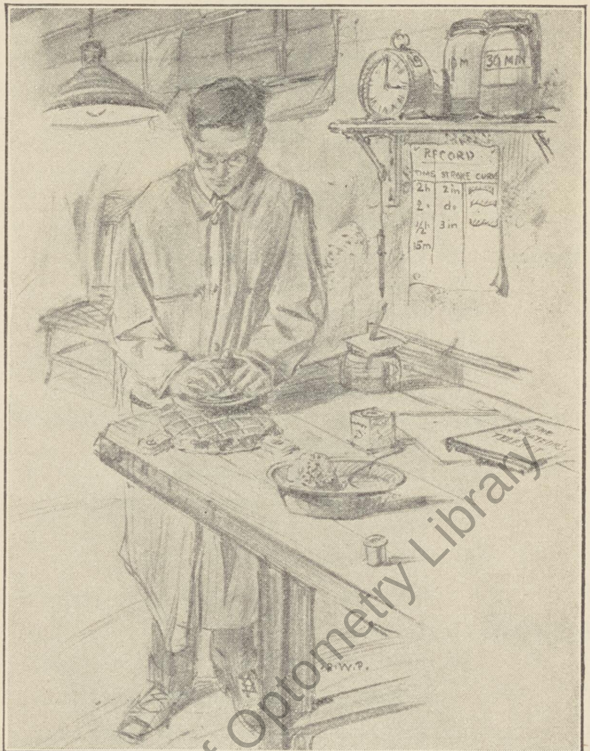
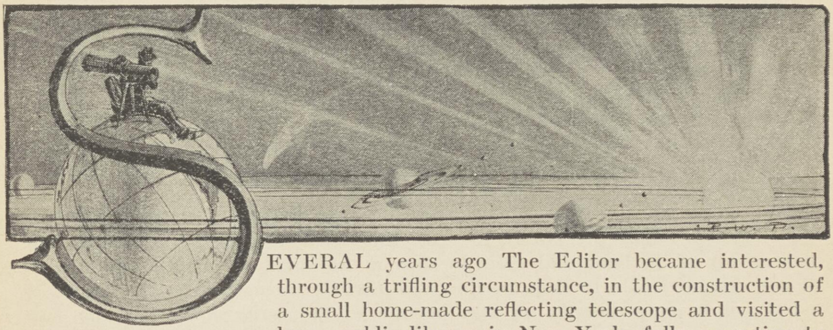


3 A. M. AND STILL AT IT

Here Porter, the artist, depicts the enthusiast as utterly absorbed in the most exacting and interesting part of the work —parabolizing the mirror. The cellar is the best place to work because its temperature is fairly uniform.

PREFACE



SEVERAL years ago The Editor became interested, through a trifling circumstance, in the construction of a small home-made reflecting telescope and visited a large public library in New York, fully expecting to draw out an armful of treatises on the subject with a view to reading up before attempting the venture.

Now it is a rare thing in these days of plentiful books and treatises on about everything under the sun, when one cannot easily lay hands upon at least a dozen books on a given subject, however obscure that subject may be; generally, in fact, the difficulty lies in eliminating all but the best one or two of them.

What, then, was The Editor's surprise on making the discovery that there was only one thoroughly practical book in the English language on telescope making for the amateur. By "practical" was meant a book which covered the subject in the detail which successful work demands and which bore the earmarks of preparation by someone whose experience in the art was not limited perhaps to the perusal of an encyclopedia article about it. That book was *The Amateur's Telescope,* most ably written by the Reverend William F. A. Ellison, Director of Armagh Observatory in Northern Ireland and veteran mirror maker. It proved to be a gold mine. With its aid work was soon commenced on a modest mirror of 6-inch diameter.

At this juncture The Editor discovered Russell W. Porter of Vermont. This gentleman, skilled by years of experience in the same work, gave willing ear to certain frantic appeals for assistance and advice, and in due course the little mirror was completed. And then a larger idea took shape. Why not, with the book by Ellison, the experienced assistance of Porter, and the pages of the *Scientific American,* attempt to popularize amateur telescope making as a widespread hobby? Such a hobby, it was thought, would be likely to make serious, dignified appeal to a rather unusual class of men. For it demands a modicum of skill and patience—enough to exclude the trifler (but not enough to have stumped hundreds of people in all walks of life who enjoy creating things of real beauty and worth with their own hands). Finally, the end-product would be an instrument capable of unlocking the majesty and

grandeur of the whole visible Universe outside of this little mote we inhabit. The idea made appeal.

Largely to enlist the interest of the potential amateur the three articles which form the opening chapters of the present volume were prepared by Porter and were published in the *Scientific American.* There was no pretense that they were complete in themselves, for arrangements had already been made to reprint with them, between the same two covers, most of Ellison's work *The Amateur's Telescope,* obtainable only in Great Britain. In his excursion through these preliminary chapters the reader will therefore kindly bear in mind that the instructions for the various operations involved in making a paraboloidal mirror will be complete only when Porter's and Ellison's contributions have both been studied.

In taking up the work of telescope making without previous experience the beginner ought preferably to read this treatise twice—once to get the general lay of the land, and again to clear it thoroughly of mental underbrush. It may be advisable to skip, in this concentrative second excursion, all those parts not bearing directly on that portion of the work which logically falls to the tyro rather than to the advanced worker. Only those who have "been there" can speak with conviction concerning the inadvisability of starting with a large mirror. In the hypothetical race one beginner making first a 6-inch mirror and later a 12-inch, will finish both mirrors before another beginner could finish in satisfactory style a 12-inch mirror were it his first attempt. On the whole, it has been said with fair accuracy that a man who is handy enough to make a good radio or do his own automobile repairing, and who will exhibit patience, will succeed at mirror making. However, it is frankly not suitable work for those who have five thumbs on either hand.

It is now, as this preface to the second edition of the book is prepared, nearly three years since the popularization of the work was commenced by the *Scientific American.* The results have been most gratifying. Enthusiastic amateurs exist in every state and in many foreign nations. We are in constant correspondence with them, they call at the editorial offices when they are in the metropolis and we find their eager interest in the telescope making hobby a constant source of inspiration. Even the professional has now willingly joined hands with us; for no scientist is more unassuming and natural in his contacts with his fellow men of all stations than the professional astronomer. Perhaps familiarity with the scale of the Universe, and a knowledge of the comparative unimportance of man in it, help confer that boon which is denied to some whose existences are too closely rooted in the narrow confines of the earth. Thus we have, as the reader will see, the phenomenon of professional astronomers contributing to a book on a hobby for amateurs; and presently, we hope, some of these professionals will themselves take up telescope making and qualify as amateurs in their own right.

Before closing this section a short sketch concerning each contributor may prove to be of interest to the uninitiated reader.

Dr. Harlow Shapley, who contributes the Foreword, is Director of the extensive observatory at Harvard College and is widely known for his dis-

coveries concerning the size of our Galaxy. He is one of America's foremost astronomers.

Russell W. Porter, author of Part I, and general collaborator with The Editor on the whole book, was born in Vermont and studied architecture at Massachusetts Institute of Technology. Following this he made eight trips to the Arctic with the Peary, Fiala-Ziegler and Baldwin-Ziegler expeditions, as artist, astronomer, topographer, surveyor, or collector for natural history. During the World War he was engaged in optical work at the United States Bureau of Standards. He is now Optical Associate of the Jones & Lamson Machine Company, too well known in the mechanical world to need further mention. He devoted much of his time there to the "screw-thread comparator" for the development of the optical parts of which he was originally responsible. We amateurs may well look to Porter as the leading genius of the American amateur telescope makers. His chapters on making a flat, a Cassegrainian telescope, and an eyepiece have never been duplicated, so far as The Editor knows, in any treatise. This is especially true of the chapter on the Cassegrainian, for it is believed that no similar instructions exist anywhere.

The Reverend William F. A. Ellison, around whose minute and explicit instructions for mirror making (Part II) the present volume was originally constructed, was formerly Rector of Fetherd-with-Tintern, but has been Director of the observatory at Armagh in Northern Ireland since 1918. This venerable masonry structure, or rather group of structures, including a residence and housing several telescopes, was built some time before the year 1800. Among the telescopes still preserved there is a six-inch reflector formerly owned by the well-known amateur astronomer King George III of England, of whom it might be said that he knew his stars better than his colonies. The Reverend Mr. Ellison took up telescope making as an amateur, and he still retains the amateur point of view. But the world, once it discovered the excellence of his mirrors, soon trod the traditional beaten path to his door to obtain them. The beginner, in making his first telescope, will find the bulk of his practical, working instructions in Ellison's treatise (pages 72-179) and should con these pages over and over.

Professor Charles S. Hastings of Yale, who contributes Part IV, has been intimately known to two generations of foremost optical workers. During many fruitful years he was one of a notable trio who together produced many of the world's largest and most famous telescopes. Of the trio, Dr. Hastings calculated the optical curves and contributed the necessary theoretical work; MacDowell, of the famous Brashear organization in Pittsburgh, contributed the craftsmanship; while Brashear himself popularized the work, also attending to the human and other relations involved.

Dr. George Ellery Hale, who describes solar research with the remarkable spectrohelioscope which he has developed, has frequently been characterized as America's foremost astronomer. Until his health recently forced him to lighten his chosen work, he was Director of the great Mt. Wilson Observatory. To list, even in outline, his honors and achievements would demand an

entire page. The interested reader will find them mentioned in "Who's Who." Dr. Hale, whom all the world regards as a professional, likes to regard himself as an amateur. He is keenly enthusiastic concerning the interest recently aroused in amateur astronomy through the channel of amateur mechanics, and only the limitations of his strength forbid him from lending direct assistance to the humblest beginner.

Dr. Elihu Thomson, whose article on the theory of the polishing operation appears as a part of the Miscellany, is known equally well to science and to industry for his long list of researches and discoveries involving both. The invention of electric welding is but one of more than five hundred inventions credited to him. Though engaged in the active direction of the great Research Laboratories at Lynn, Massachusetts, to which the General Electric Company has given his name, he has never lost interest in one of his early hobbies—amateur telescope making. In past years he has made several refractors, including, of course, the objective lenses for them.

Professor G. W. Ritchey, a few of whose remarks appear in the Miscellany, is without doubt the world's most expert mirror maker, his largest piece of work being the 100-inch mirror at Mt. Wilson Observatory. Though engaged in exacting research on a new attempt to reach greater powers of telescopic magnification, he is nevertheless keenly interested in the popularization of the work among amateurs.

Clarendon Ions, who tells how to convert a Model T Ford into a telescope, is a Southern business man who for many years has made amateur optics his hobby. He is connected with the unique Southern Cross Observatory at Miami, Florida, devoted wholly to engaging the interest of the public in astronomy.

John M. Pierce, who tells how to make a simple telescope, is Director of Vocational Training in the Springfield, Vermont, High School—work involving machine shop practice in a large measure. He is a graduate of the Carnegie Institute of Technology in Pittsburgh and is a member of the original group known as the Telescope Makers of Springfield.

A. W. Everest, who describes the HCF polishing lap, is connected with the General Electric Company at Pittsfield, Massachusetts. Highly original himself, it is not remarkable to those who know him that he has hit upon an original method of hastening a previously fatiguing task. He has made at least eight excellent mirrors and knows whereof he writes.

And now, let us take up the actual work.

New York, July, 1928.

Albert G. Ingalls,
Associate Editor, Scientific American.

FOREWORD

By Harlow Shapley, Ph.D., Director, Harvard College Observatory

"I set myself to work", wrote the great Christian Huygens, one of the earliest of amateur telescope makers, who, inspired by Galileo's telescopic revelations, proceeded to reveal celestial marvels on his own account, and in 1659 unravelled the secret of Saturn's rings—"I set myself to work with all the earnestness and seriousness I could command to learn the art by which glasses are fashioned for these uses, and I did not regret having put my own hand to the task".

"And now that I, too, have fashioned some glasses," the amateur instrument maker may inquire, "what next?"

Three things are next; the first is inevitable, the first two are natural, and all three are possible. The first is to feel satisfaction that you have created something with your own hands. The second is to indulge your curiosity, and incite that of your friends, by using your equipment on the objects for which it is designed; but, in so doing, keep in mind that pride of manufacture is justifiable, but that humility and wonder are the appropriate attitudes in contemplating the stars.

The third privilege of the amateur, who has followed the book and his own intuition in constructing astronomical tools, is to use his product advantageously for science. To do so effectively, he must be sincere and have both freedom and spirit. Assuming that you who read this are so gifted, I shall make some suggestions.

First, if you have "fashioned some glasses" into a telescope of three inches aperture or larger, you can do valuable work on variable stars. The American Association of Variable Star Observers would welcome you to its international membership, give you instructions, charts and encouragement. And if you are of the right stuff, within a few months you should become, in your extra evening hours, one of the contributors toward the solution of some major astronomical problems, such as the nature of stellar variability and the evolution of stars.

If the Earth and the Moon attract you more than the remote telescopic stars, and if you have access to accurate time by observatory clock or radio, you are invited to learn the simple technique of occultations—that is, the accurate timing of the eclipsing of stars by the Moon. It is only of late that we have come to realize the important work that the serious amateur astronomer can do in helping to determine the Moon's position by observing the predicted occultations. Your observations will be directed and studied by professionals; and you will be aiding in a fundamental research—the measurement of irregularities in the rotation of the Earth and the lengthening of the terrestrial day.

Second, if you have fashioned (or bought) and mounted a very rapid photographic lens, in which the ratio of focal length of aperture is 3.0, or 2.0, or even less, you are invited to join the select ranks of astronomical sportsmen and go gunning for photographs of shooting stars. Photographing the

shooting stars costs no more than trout fishing in the Adirondacks, or hunting mountain sheep in the Rockies, or angling off Catalina Island; but it should have much the same appeal and difficulty, and a greater thrill when success arrives. It is not hard to see shooting stars and make unreliable visual observations of them; but it is an art, mastered by few amateurs or professionals, to photograph the elusive intruders in our upper atmosphere and thereby make permanent and accurate records. We must have more meteor photographs. One hundred thousand plates in the Harvard collection have been examined, and have revealed only a few hundred meteor trails. They form the most important collection of such data in the world, and the importance lies largely in the fact that astronomers now see the great significance of meteors in the problems of interstellar space, of comets, and asteroids, of the nature of nebulae, and of the origin and maintenance of starlight. Meteors are fundamental and little known; they are the game of the astronomical sportsman, and if he can work with others of his kind, so much the more important his contribution.

Third, if you have fashioned some contrivance for the better recording of meteor paths observed visually among the stars, then you should get acquainted with the American Meteor Society, and the work it tries to do. You will find that there is good systematic work to be done in that field without camera and without telescope.

In summary, if you have the time and spirit for it, you can crown the zeal you have displayed in making an astronomical instrument by using it intelligently and constructively on important projects. If you communicate your earnest astronomical aspirations to any of the observatories, you will be freely counselled. The professional astronomer has gained too much from the amateur in the past to disregard him at this time, when many useful contributions can be made by the man whose hobby is astronomy. But remember that constructive work is only one of three privileges of the amateur telescope maker. The second may be the most important—to look into the heavens with uncovered head and humble heart.

AMATEUR TELESCOPE MAKING

Part I.

CHAPTER I.

Mirror Making for Reflecting Telescopes

By Russell W. Porter, M.S.
Optical Associate, Jones & Lamson Machine Company

In the reflecting telescope, *the mirror's the thing.* No matter how elaborate and accurate the rest of the instrument, if it has a poor mirror, it is hopeless. Conversely, a good mirror, even if it is crudely and simply mounted, makes a powerful and efficient astronomical tool.

We are concerned in this chapter with the shaping of the telescope mirror.

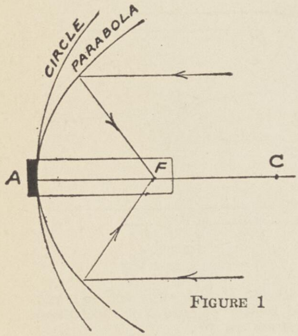


Figure 1

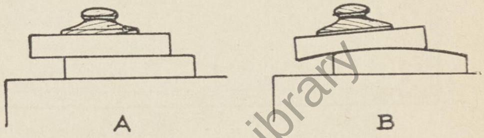


Figure 2

Figure 1. THEORY OF THE MIRROR. *Many find it difficult to understand why the focal length is only one-half of the radius or distance to the center of curvature, while in the shadow test the light is focused at the center of curvature. In the first case the rays are coming from a star, at almost infinite distance, and are therefore virtually parallel, while the rays that reach the mirror from the pinhole are divergent (radii). In this diagram, let us imagine we could grasp the two parallel rays indicated and actually pull their right-hand ends together until they touched the point C. As we drew them in, the angle at which they would now meet the mirror's surface would change, and since light is reflected away at the same angle at which it strikes a mirror, the reflected rays would shift at the same time from F to C, at double the distance of F.*

Figure 2. WHY THE CURVES DEVELOP. *The upper disk tends to hollow out because at the extremities of the strokes the abrasive effect on both disks is increased. This is due to the overhang and to the consequently increased pressure on the central portion of the upper disk, as well as the marginal part of the lower.*

This consists solely in giving one side of it a concave, polished surface. This surface is to be so very nearly spherical that we shall first attempt to make it precisely so; and at the very last we shall alter it to the kind of surface familiar to us all in automobile headlight reflectors, and known among the highbrows as a paraboloid of revolution.

Such an automobile headlight has the property of throwing out from a concentrated source of light placed at a focal point near it, a beam of parallel rays. (See Figure 1.) We shall, however, use this reflector the other way around, that is, by receiving parallel rays of light from a distant object (star); and by reflecting them from a properly curved mirror we shall bring them to a point or focus (F, Figure 1).

Our curve, however, is so small a portion of this widely sweeping parabola (the black area represents the mirror) that it is extremely shallow, and so it nearly coincides with the superimposed spherical curve. At first, therefore, we shall seek to hollow out a spherical curve, later deepening it very slightly into the paraboloid.

Since the angle of incidence of a reflected beam of light is equal to the angle of reflection, the parallel, arriving rays will be reflected approximately to a focus whose length may be regarded as one-half of the radius of curvature, C-A, Figure 1.

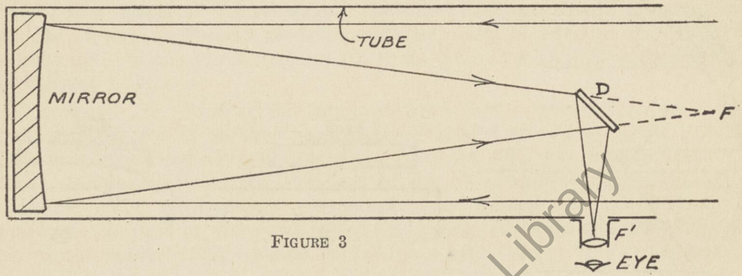


FIGURE 3

FIGURE 3. WHY A DIAGONAL IS NEEDED. *Without it the rays would theoretically come to a focus at F, where the observer's head would eclipse the light from the object. The diagonal mirror, or a prism, reflects them to F'.*

Enlarging the mirror of Figure 1, A, we have in Figure 3 the essentials of the Newtonian, reflecting telescope. Light from a distant object falls down the tube to the mirror, and normally would, by reflection, produce an image at the focus, F. The converging rays are, however, intercepted at D by a small diagonal mirror or prism that delivers them to a lens called an eye-piece at the side of the tube, where the image is examined.

I will take as our standard, a mirror six inches in diameter, having a four-foot focal length. The beginner is not advised to essay a larger mirror for his first effort, since his difficulties will be found to multiply quite disproportionately as the diameter increases. If two flat glass disks (A, Figure 2) are ground together, one over the other, with an abrasive between, lo and behold!—the upper one becomes concave, the lower one convex. This is because the center receives constant wear, while the outer portions, overhanging part of the time, receive less wear. In the illustration the length of stroke is somewhat exaggerated.

A straight, back-and-forth stroke, in which a given point on the upper disk moves across one-third the diameter of the lower, has the property

of holding the two surfaces spherical. This is due to the fact that spherical surfaces are the only ones which remain in continuous contact at every point when moved over each other in any direction. This fact is a veritable godsend to the amateur—and to the professional, too, for that matter—for he may go confidently forward through the different stages of grinding and

FIGURE 4

PREPARING THE PITCH LAP

Melted pitch is being poured on the convex, upper face of the tool. Note the temporary collar of wet paper, which acts as a retaining wall for the pitch until it cools. Tool and mirror should previously have been placed in luke warm *water. If pitch is poured on a cold tool it will "set" so rapidly that there will be little time to make it conform to the curve of the mirror. But if the two disks are somewhat warm, there will be about ten minutes time in which to make a lap that will preserve good contact. Thus the worker may "take it easy" and do it correctly. Keep cold drafts away from the job. Warm water striking cold glass is not likely to break it, but cold water striking warm glass may.*

polishing with the knowledge that his mirror will come out nearly as it will be when it is finally deepened into a paraboloid.

The depth of the curve increases with grinding, and it is gaged with a template of the proper radius. Since by our rule, the radius, A-C, Figure 1, of the curve of the glass is twice its focal length A-F, a template is made from tin, with a radius of twice 48 inches, or 96 inches. Therefore a stick

of wood (not a string, which would be elastic) should be tacked to the floor at one end so as to pivot, and a knife point held at the opposite end, or a sharpened nail driven through at the proper distance, should be used to scratch the desired curve to which the tin should be cut. For our six-inch mirror the hollow will come to about .05 inch deep.

The lower disk of glass is fastened to a pedestal or to a weighted barrel so that one can walk around it in grinding, or it may be held be-

FIGURE 5

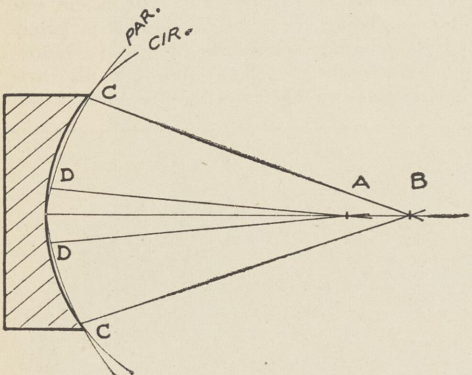
CUTTING CHANNELS IN THE PITCH LAP

Use a flexible straight-edge and a sharp knife. Keep everything wet, to minimize sticking of the pitch. In spacing the channels, precision serves no particular purpose. Do not center them, in any case. After the lap is formed and the channels are cut, leave the mirror on the lap until the tool, pitch and mirror have regained uniform room temperature. It should then be "cold pressed," or weighted, to insure the establishment of an even contact, which may have been disturbed during the cooling process.

tween one removable and two fixed buttons on the corner of a stout bench or table. (See frontispiece.) Using melted pitch, a round handle is attached to the upper disk, which is first heated in cold water to a slightly unpleasant warmth for the hand, taking care that no cold water drops fall on the warmed disk, for they might break it.

The grinding is done by placing wet carborundum grains of successively

finer sizes between the two disks, care being taken after each size is used to wash all parts of the work entirely free of the larger sized grains, which would otherwise scratch the disk. The strokes are straight forward and back, the center of one disk crossing that of the other. The glass also rotates bit by bit in the hands, in order to present a new direction for each stroke; and from time to time, in order to prevent the wearing of the glass unsymmetrically, the worker shifts positions around the pedestal; or, if working on a bench, he turns the lower disk, called the "tool" (we shall discard this tool at the end) to a new position.



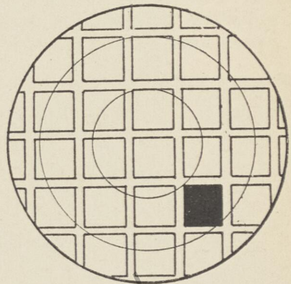


FIGURE 6

HOW MUCH HAVE WE PARABOLIZED?

The radius of a parabola shortens as its vertex is approached. Therefore the zone of the parabola near the edge, C, C, may be regarded (in practice) as part of a sphere with radius C-B. The central zone is regarded as part of a smaller sphere (shorter radius) with radius D-A. In the shadow test we can actually measure the distance A-B with a scale, and from this we can work out the amount that we have deepened or parabolized the center of our spherical mirror.

A TYPICAL PITCH LAP FOR A SIX-INCH MIRROR

The black square represents a facet removed from the lap in an effort to treat a depressed zone. Thus there would be less abrasion over the path traveled by this region as the mirror was rotated in polishing, and a zone (see rings on drawing) would tend to be raised above the general level of the glass.

Each grade of abrasive is used long enough to remove the coarser pits by the preceding grade, and it will save much time and labor in the polishing if a small quantity of wash 6F ("sixty minute") emery is used after the Number 600 carborundum.

All the preceding work is covered in great detail by Ellison in "The Amateur's Telescope," Part II of the present book, which at this time is the only modern work of this nature available in America.

The bench and both disks are now thoroughly washed in order to remove all traces of grit, preparatory to polishing.

Pitch is melted over a stove. It is tempered by adding (not over the fire) sufficient turpentine until a cooled sample placed between the teeth

will just "give" slowly without crumbling, or will show a slight indentation of the thumb-nail under moderate pressure. The pitch is poured (Figure 4) over the tool, which has been warmed in water, and dried, and when it is partly cool, the glass is wetted (in warm water) and pressed down on the pitch until perfect contact is obtained between glass and pitch. V-shaped channels an inch apart are now cut across the pitch at right angles to each other, to allow free access of the rouge and water to all parts of the glass. Do not center this system of channels or you may produce zones in the mirror. See Figure 6.

Rouge mixed with water is now substituted for the carborundum and the polishing is carried on to completion, using the same strokes as in grinding. The time thus far consumed in grinding should be about five hours; polishing may require nine hours, divided into "spells." Through all these operations Ellison goes with painstaking care, anticipating the pitfalls into

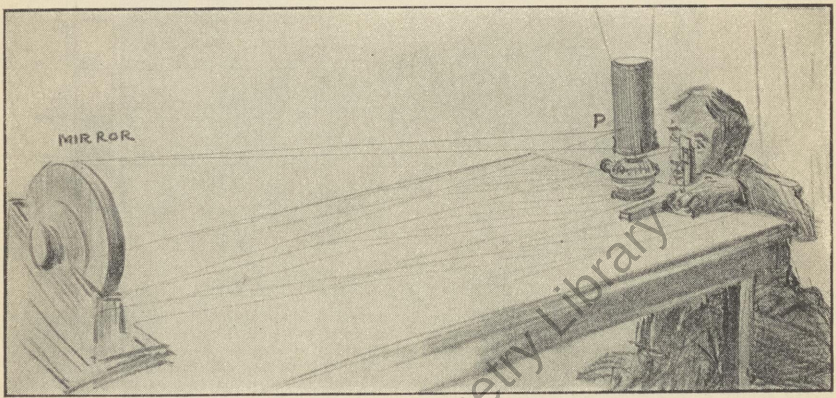


FIGURE 7

MAKING THE SHADOW TEST

The mirror does not necessarily have to rest on the same surface with the lamp and knife-edge, but all three should rest on stable supports which will not vibrate after the hand is removed from the knife-edge.

which the tyro inevitably falls. Were I to emphasize one caution over another, it would be the care required in preserving complete contact between the glass and the pitch lap surfaces while polishing.

If one-third strokes have been maintained in grinding and polishing, the surface of the glass will be nearly spherical. How shall we find out? The method I shall now describe is one of the most delicate and beautiful tests to be found in the realm of physics. By it, imperfections of a millionth of an inch on the glass can be detected, and all the tools required are a kerosene lamp and a safety razor blade! This method of testing mirrors, called the Foucault knife-edge test, was unknown until about 1850; before that time mirror makers were groping in the dark. Even the great Herschel

—father of the reflecting telescope—did not know when his mirrors were right, except by taking them out and trying them on a star.

If an artificial star made by a tiny pinhole (use a needle point) in a

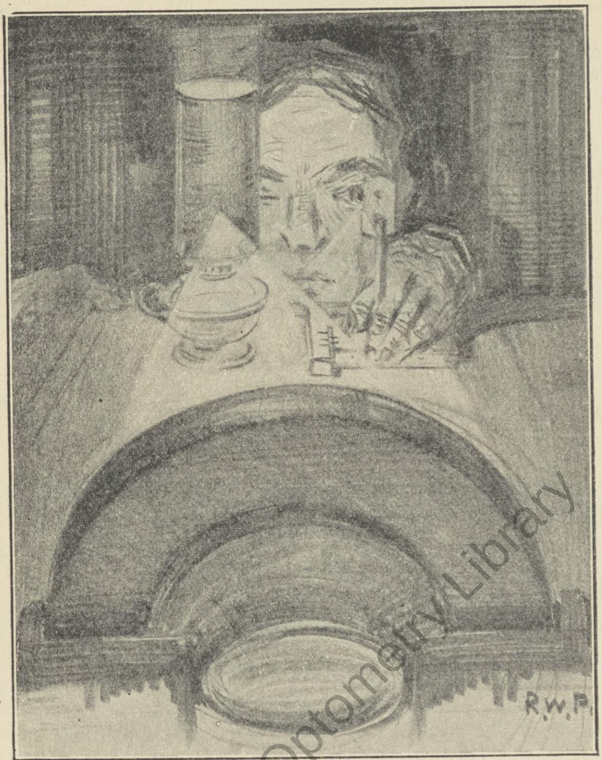


FIGURE 8

MAKING THE KNIFE-EDGE TEST

The semi-circle in the foreground is the back of the mirror, with its handle, set in a simple wooden frame-work which can be made of a packing box cut down. Beyond is the lamp with metal chimney pierced by a needle hole; also the knife-edge. The latter consists simply of a dulled safety-razor blade or any strip of metal set in a split stick of wood which is driven into a hole in a block of wood. This crude equipment serves as well as if it were elaborated with more complicated devices.

tin chimney on a kerosene lamp (an electric lamp will not be suitable) were placed at the center of the sphere of which the mirror's curve is a very small part, all of that portion of the light that emerges from the pinhole and strikes the mirror, is reflected back to the pinhole; for these light rays

are all radii of the sphere, and by reflection they must return as radii back to their source, the pinhole.

In practice, the pinhole is pushed over a little to the right of the center of curvature so that the cone of reflected light may clear the chimney and enter the eye, as shown in Figures 7, 8 and 9. The mirror is placed on its edge on some suitable support, at table height, in a fairly darkened room. The lamp and the knife-edge (mounted on a block of wood) are placed on a table as shown, and about eight feet from the mirror, viz., at its center of curvature. The lamp remains stationary.

At first, considerable difficulty may be encountered in picking up with the eye the reflected cone of light. One way is to replace the tin chimney with a glass one, walk away from the lamp, keeping it in line with the mirror, when the image of the lamp will be seen in the mirror itself. Then bring the eye forward slowly, keeping the lamp image in view, and move

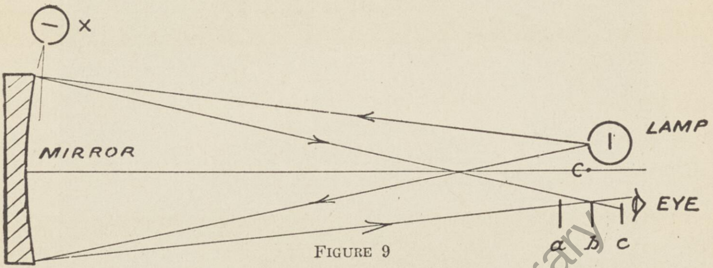


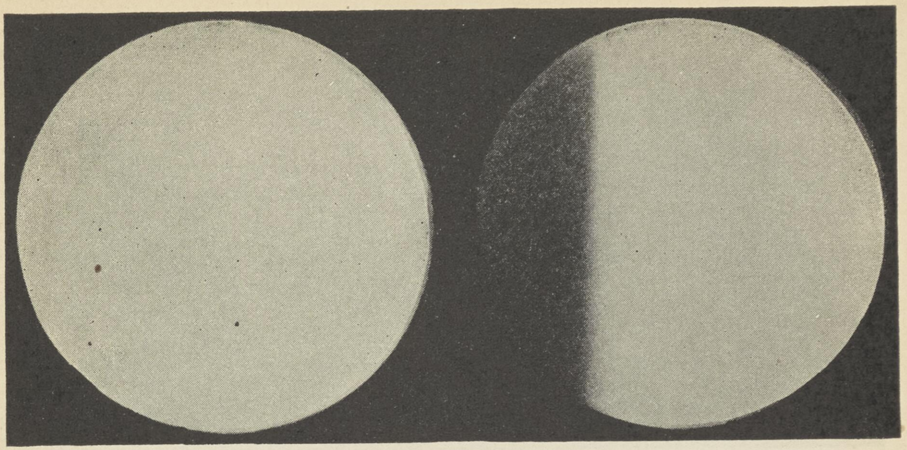
FIGURE 9

FINDING THE CENTER OF CURVATURE OF A SPHERICAL MIRROR

This is comparatively easy if the mirror is a true sphere. This point, b, can be located quite precisely. If, however, the mirror is parabolized, we speak of the "mean center of curvature," that is, half way between that of the outer zone, regarded locally as a section of a sphere, and the central zone, similarly regarded.

the knife-edge to the right until it cuts off half of the image. The tin chimney is then put on and the image of the pinhole may be picked up somewhere near the edge of the safety razor blade. As the eye approaches the position shown in the figures, this pinhole image begins to expand until a position is reached where the mirror is flooded with light over its entire surface—almost dazzling. See shadowgraph A, Figure 10. An alternate method is to use a piece of ground glass, which can be prepared by rubbing it with carborundum, to explore the neighborhood of the lamp, picking up the bright spot of light on it.

Now comes the remarkable knife-edge test. The razor blade is moved in from the left until it cuts into the reflected cone of rays. If at a, Figure 9, that is, *inside* of the center of curvature, a shadow will come in on the mirror from the left, as might be expected (shadowgraph B). If, however, it cuts the rays at c, Figure 9, that is, *outside* the center of curvature, the shadow will advance over the mirror from the right, giving appearance the reverse of shadowgraph B (or as B appears with the page turned upside down.) But *at* the center of curvature, b, the mirror, if spherical, darkens



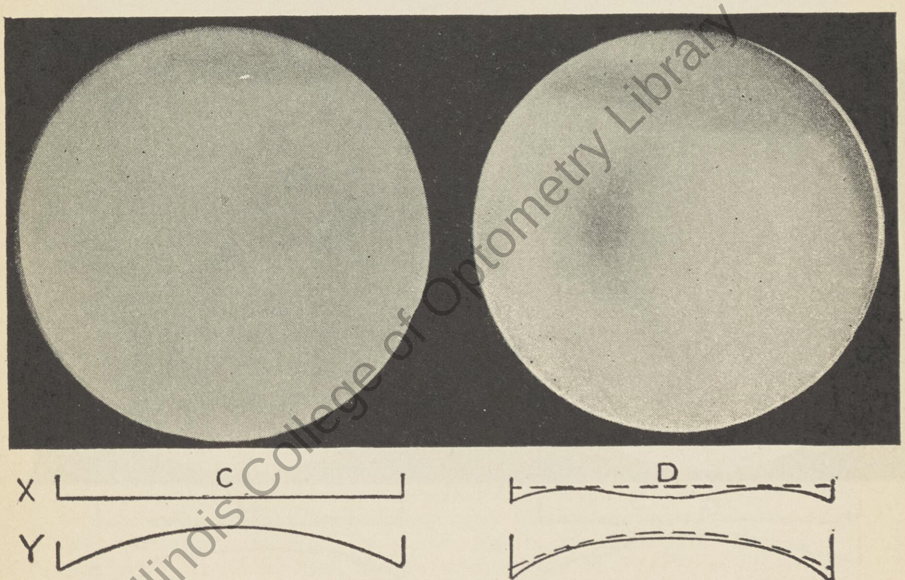
A

APPEARANCE OF MIRROR BEFORE THE KNIFE EDGE CUTS THE REFLECTED LIGHT.

B

KNIFE EDGE INSIDE THE CENTER OF CURVATURE OF THE MIRROR.

FIGURE 10



SPHERE

OBLATE SPHEROID

FIGURE 11

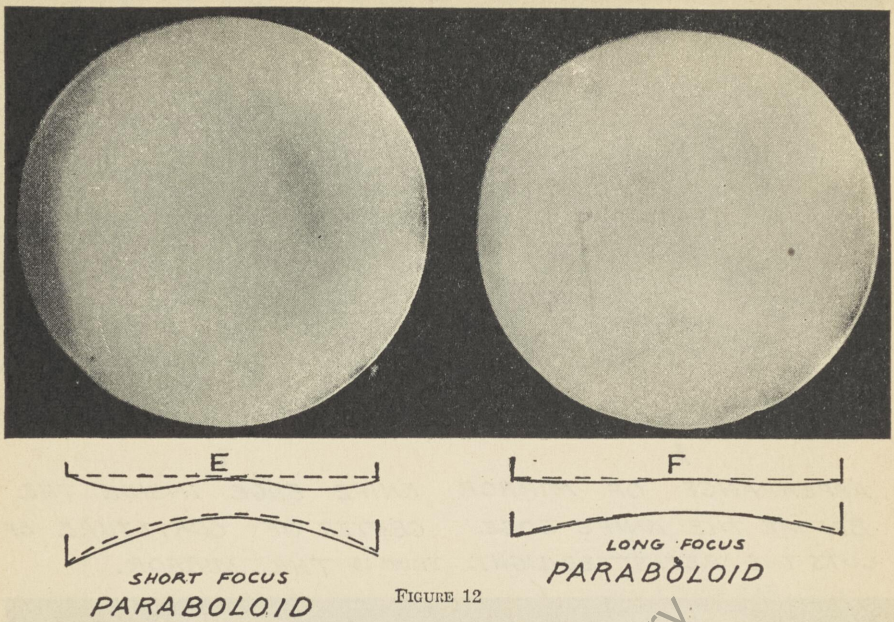


FIGURE 12

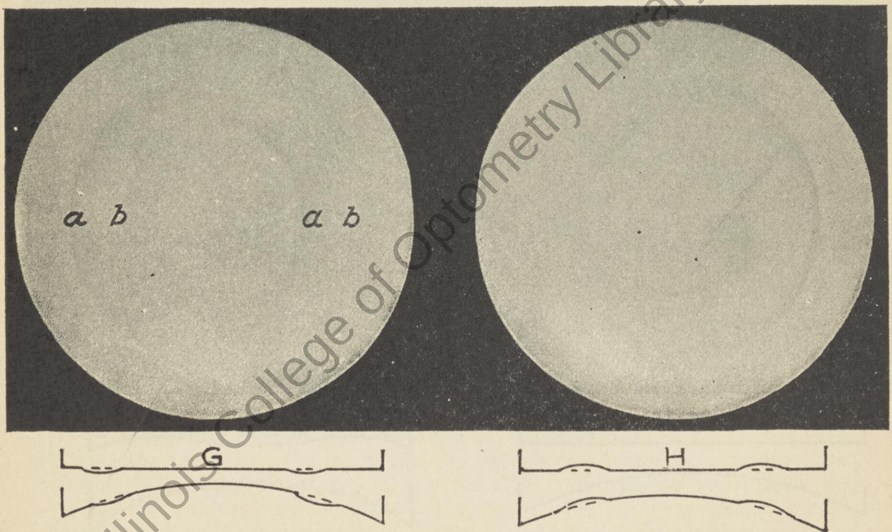


FIGURE 13

simultaneously over its entire surface, becomes evenly gray like shadowgraph C, Figure 11. As the knife-edge is moved farther, the shadow quickly vanishes. This is the simple test for a spherical surface, but it would be sheer luck if one's mirror appeared thus at the first test.

Viewed as just described, the surface of the curved mirror does not seem curved, but has the strange illusion of being flat. The observer *knows*

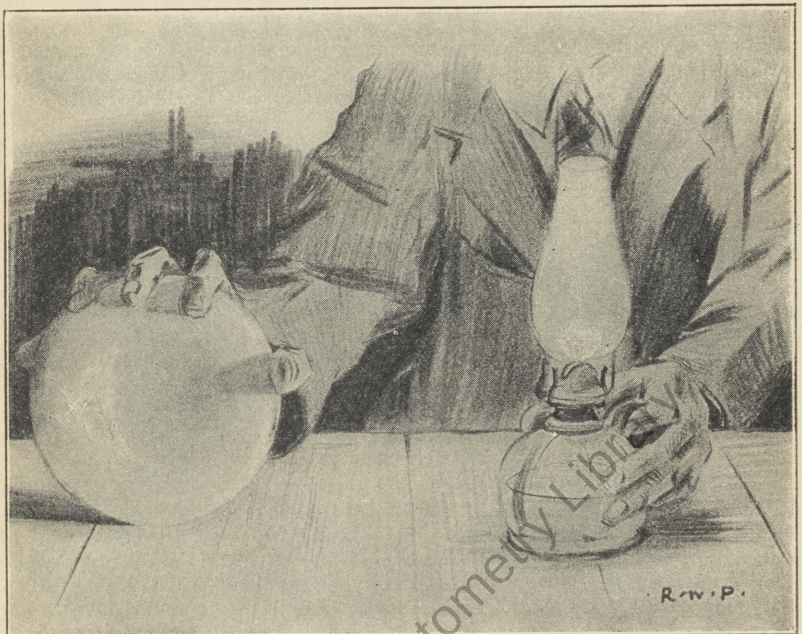


FIGURE 14

AN EFFORT TO EXPLAIN THE ILLUSION OF THE KNIFE-EDGE SHADOWS

The real source of light in the shadow test is the pinhole, which is in front of the mirror. But the mirror appears as though it were being illuminated from one side, grazingly, as in this sketch.

it actually has a section like Y, under shadowgraph C, but it *appears* flat, like apparent section X, same place.

The surface having been brought to a sufficiently fine polish and to a spherical curve, the remaining work on the mirror, known as the "figuring," consists in slightly deepening this spherical surface into a paraboloidal surface, and this is done by polishing away the center faster than the edge. The final goal is to make the mirror appear, when the razor blade is beginning to cut off the light, like the shadowgraph E, F, (Figure 12) or some intermediate depth, depending on the focal length, which need not be exact.

A common imperfection will be a raised or depressed zone, appearing like G and H, Figure 13, whose true (lower) and apparent (upper) sections are shown beneath them. In the case of the raised zone the shadow has all the reality of a flat surface on which is a raised portion in the shape of a ring, the left slopes a, a, shadowgraph G, being in shade, the right slopes b, b, being in the light, *as though* the mirror were illuminated by a lamp placed on the opposite side of the glass from the knife-edge, as at X, in Figure 9. Figure 14 is an attempt to show how this imaginary lighting, at grazing incidence, *would* produce these shadows. Here the shadow of the man's fingers is superposed over the knife-edge shadow of a paraboloid. Conversely, a depressed zone (shadowgraph H) will have its lights and shades reversed.

Other characteristic shadowgraphs shown indicate curved surfaces well known to geometers under mouth-filling names. I would refrain from repeating them here for fear of throwing the novice into a panic of discouragement, but they must, nevertheless, be labeled for purposes of identification. Perhaps it will refresh the student's memory to note again the relations of these curves as shown in conic sections.

We have already considered the sphere whose section gives a circle (near top of cone, Figure 15). Its neighbors above (unlabeled) and below are the oblate spheroid whose shadowgraph, shown at D of the series, presents a raised center and edge. The next curve is the parabola, its corresponding surface being the paraboloid, having an appearance the reverse of the oblate spheroid, an apparently depressed center and edge, like a "Life Saver" candy with its central hole filled in. *This is the surface of a perfect telescope mirror.*

The hyperboloid, corresponding to the hyperbola (Figure 15) is not shown in any of the shadowgraphs; its shadows are those of an exaggerated paraboloid, that is, quite dark, with the crest of the raised area nearer the edge of the mirror. A paraboloidal mirror of short focus gives the stronger shade (shadowgraph E); a mirror of long focus gives a fainter shade (shadowgraph F). Our mirror, with focal length approximately eight times its diameter, is about intermediate.

There is something uncanny about these shadows and shadowgraphs. As before mentioned, they should all be interpreted *as though* illuminated by light coming in from the right. But if one can force one's self to imagine these shadows as produced by light coming from the left, they will give an impression exactly the obverse. For example, in the case of the zone (shadowgraph G), one can change its appearance from a bas-relief to an intaglio, like shadowgraph H, by imagining it lighted from the left; and with a little experience one can make it perform in either manner at will. The rule is to consider the light coming from a direction opposite to the knife-edge. Ellison is almost unique among mirror workers in placing the light on the left and the knife-edge on the right.

Now all of these possible surfaces into which one's mirror may develop, are to be treated in the same way—the apparently raised portions are worn down to an apparently flat surface. There are several ways of accomplishing

this result and all are described by Ellison in Part II, at greater length than the present space could possibly permit. In general, a zone may be reduced by removing a part of the pitch lap, for it is evident that a square of pitch removed as shown in Figure 6 would tend to raise a zone on the mirror. The danger here is in producing unexpected zones, and the drawback of having to remake the lap (always a fussy job) if the altered pitch fails to correct the glass. Suffice it to say that, as explained in Part II,

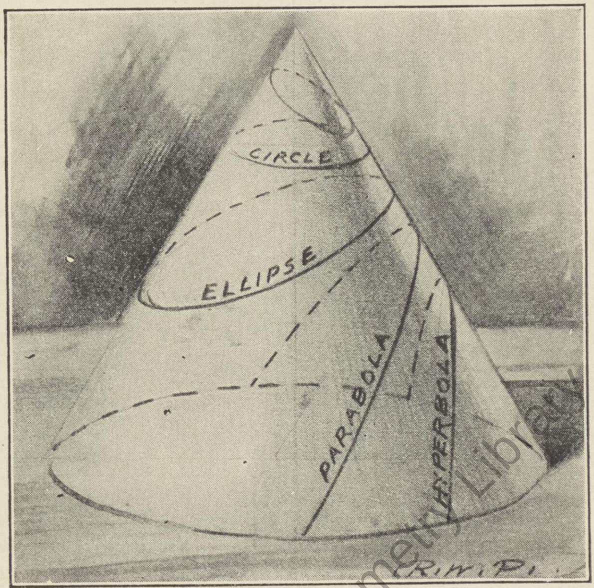


FIGURE 15

THE VARIOUS CONIC SECTIONS

The curves that may arise as the mirror is worked may be expressed as sections taken at various parts through a cone. For purposes of instruction an actual cone of wood may be cut across on each of these planes. It is well for the worker to become familiar with the nature of each type of curve or conic section. Any good encyclopedia describes them.

Chap. V, there are several strokes and positions of the glass overhanging the tool that will bring almost any surface to that of the desired sphere, ready for the slight deepening into a paraboloid, without changing the lap.

This is the hardest, but at the same time the most fascinating, part of mirror making. Any one of these surfaces is so close to the sphere that no mechanical means could detect a difference between them. And yet, under the knife-edge, each type stands out glaringly with its own characteristic shadow—never to be forgotten when once seen.

Let us now assume that the mirror has been brought spherical—that it appears flat, under test. The curve now to be sought belongs to type E, F (shadowgraphs). This is very close to the sphere—so close that but a few moments' polishing with a long stroke, or by letting the glass overhang the tool sidewise, will produce it. *Frequent testing is therefore essential during this crucial work of figuring the mirror.*

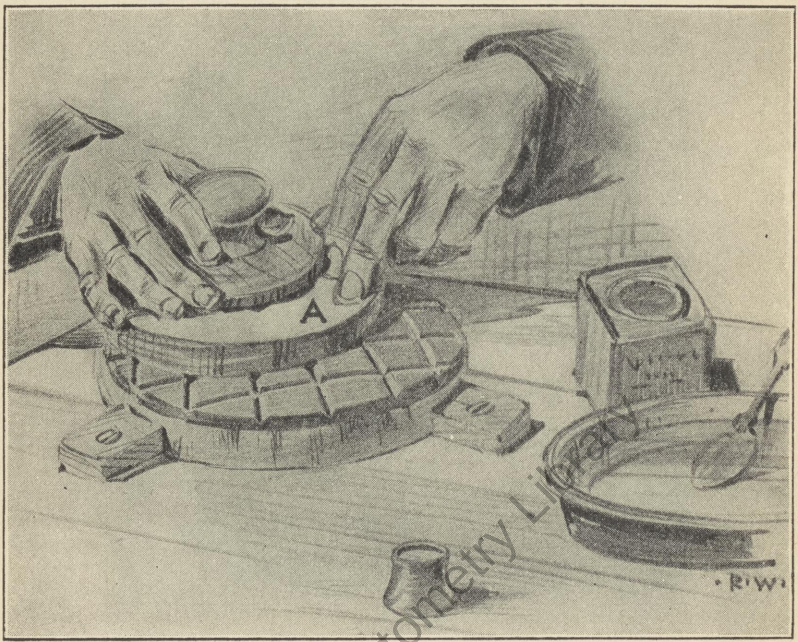


FIGURE 16

PARABOLIZING BY OVERHANG

*The commonest of the several possible methods. Light side pressure is being exerted with the left hand. (It is an interesting sidelight, that in making this sketch, the artist, lacking a model at the moment, posed as his own model. A mirror was used in order to obtain the proper appearance of the free hand unemployed in sketching. When it came to sketching the other hand, two mirrors were employed, thus again leaving the sketching hand free.—*ED.)

In Figure 6, the two curves represent sections of a sphere and of a paraboloid. It is evident that the parabolic curve is flatter at the margins, C, C, of the glass than at the central portion, D-D. Therefore light reflected from the pinhole will bring the rays from C and C to a point at B, on the axis of the mirror, further away than the point where the deeper part of the curve, D-D will focus them.

The distance between A and B is given from the equation, AB equals

the square of the radius of the mirror, divided by its radius of curvature. Substituting for our six-inch mirror of four-foot focal length, we have, AB equals $(3)^2$ divided by 96, or 9/96, which is about one-tenth of an inch.

We now diaphragm out all of the mirror except a half-inch around the margin, and mark on the table the position of the knife-edge when the light darkens equally over the exposed portions. All of the mirror is then covered except a central portion two inches in diameter, and the knife-edge test is again applied similarly. This time, if the surface is correctly parabolized, we shall have to move the knife-edge toward the mirror one-tenth of an inch, as above determined. In both of the above tests, what we are really doing is to select limited parts of the paraboloid and regard each part

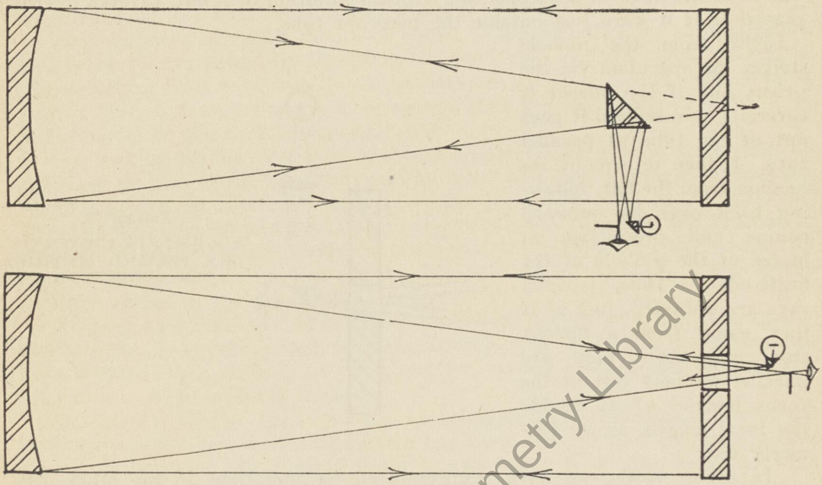


FIGURE 17. TWO METHODS OF TESTING AT THE FOCUS.

as locally spherical; and then determine the degree of parabolization by ascertaining the difference in focal length of the respective spheres.

Silvering is now in order. It was some time before I produced a good, tough, silver coating, but if I had had access to the information in Part III there would have been no trouble.

Finally, if a lacquer diluted six times with amyl acetate, is poured over the mirror and allowed to dry with the glass on its edge, the lustre of the silver will be prolonged for years, without in any way impairing its optical properties.

I have intentionally selected the method of testing at the center of curvature as being the favorite among amateurs, notwithstanding the fact that it is not as rigorous as testing at the focus with an optical flat. Testing at the center of curvature is capable of yielding an acceptable glass in a reasonable time before the worker's patience has become quite exhausted. It

is far better in the interest of the amateur astronomer that he go far enough in the work to see and appreciate what a fair mirror will show him in the heavens, before he bogs down in the slough of despond and throws up the job as impossible.

A few years ago I tried out the method just mentioned with fifteen mechanics (taken at random from the industrial shops of Springfield, Vermont) and they all produced acceptable mirrors, and nearly all finished their mountings.

A reference to the method of testing at the focus will be interesting to one who has figured his mirror at the center of curvature. The set-up is shown in Figure 17, at the top. The optical parts are arranged just as they will be in the finished telescope, but with the addition of a flat, silvered mirror, placed as if it were just outside the telescope tube.

Light from the pinhole strikes the speculum via the prism, and if the mirror is correctly parabolized it goes out of the tube as parallel rays. It then returns by reflection from the flat, following back over its outward course and producing an image of the pinhole at the knife-edge. Thus, parallel rays are obtained, just as if they came from a distant star, and since they are parallel we may test at the focus instead of at double the focal length, as we formerly did.

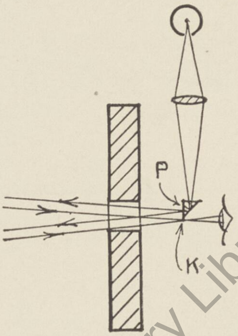


FIGURE 18.
A MODIFICATION OF THE SECOND METHOD OF FIGURE 17.

In other words, we have manufactured parallel light in the laboratory. This is the most rigorous method of testing, but it requires a flat the size of the speculum, and the flat is the most difficult of all surfaces to make.

In testing at the focus the pinhole and knife-edge must be brought close together in order to avoid the necessity of providing a large diagonal. This is accomplished by placing a small (¼″) prism over the pinhole, as shown in the upper figure. I parabolized about 100 6-inch mirrors by this method, modified as shown in the lower drawing. Here the flat had a central hole and the pinhole and knife-edge were located just back of it.

If these two arrangements are closely studied it will be seen that two reflections are avoided by the second. In the first, the light is reflected from the pinhole to the large diagonal, thence to the concave, thence to the flat, and returns over the same course in reverse order, to the knife-edge. In the second, however, the light goes from the pinhole to the concave, thence to the flat, and return via the concave, back to the knife-edge.

Thus in the first method there are five reflections, against three in the

second. Not only is this a great saving in light, but the ease with which the second arrangement may be put in adjustment and the image found shows at once the advantage of the second method.

An additional refinement is the introduction of a condensing lens between the light-source (I used a cylindrical acetylene flame) and the pinhole, and this is shown in Figure 18. This allows the lamp, with its unavoidable heat, to be removed from the vicinity of the flat.

I covered the front of the small prism P, with tinfoil in which the pinhole was perforated. Incidentally, the tinfoil was made to overlap the edge of the prism slightly at K, and thus it became the knife-edge itself. In this way I was enabled to keep both pinhole and knife-edge within only one-eighth of an inch of each other, permitting the use of a flat which happened to have a central hole less than an inch in diameter.

The amateur's attention should be called to the fact that the set-ups shown in Figure 17 are primarily intended for producing parallel light *artificially*. The returning light rays from the large flats are precisely like the light coming from a star, but with the great advantage that the rays are not affected by disturbances of the earth's atmosphere.

For testing at the focus, an ordinary engine lathe can be made into an excellent testing bench by removing the head and tail stocks, mounting the concave mirror on a suitable support at the head stock end of the lathe bed and fastening the flat and the lamp to the cross slide. Anyone who is familiar with the engine lathe will realize at once that the pinhole and knife-edge can thus be maintained in perfect control, both toward or from the concave, and at right angles to the axis of the mirror.

Nothing has been said here about scratches, effects of changed temperature on the glass, where best to work, testing with an eyepiece, the dreaded turned-down edge, sticking of the glass, the various strokes and altered laps, and so on. Ellison covers them all.

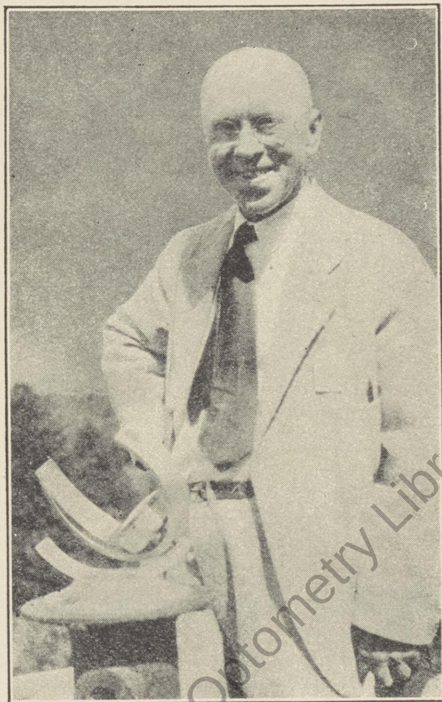
Sir Howard Grubb, the well-known English maker of telescopes, is credited with the remark that "when the mirror has been brought to a complete polish, the work is about one-quarter done." And while it is true that the long interval of figuring with its interminable testing, tries the soul of the amateur, let him take pride in the fact that he is dealing with—and controlling—minute errors a thousand times smaller than those dealt with by a mechanic or machinist; and in the satisfaction of knowing that with this mirror made with his two hands he will be able to see the polar caps of Mars, Jupiter's bands, Saturn's rings, nebulæ, clusters and double stars—an instrument that would have excited the envy even of Galileo and Newton.

My experience has been this, that anyone who can use his hands, is possessed of moderate patience and sufficient reasoning ability to interpret the knife-edge shadows, can make a good mirror. Without these attributes he had better forego the venture.

Mirror making has many points to commend it. The tools are easy to make. The cost of materials is (compared to results) low. The work may be carried on at odd moments, day or night and in any available room of the home. In short, it contains the elements of a real indoor sport.

STELLAFANE

Stellafane, or "Stellar Fane" (shrine to the stars) as it was formerly called, is the little club-house-observatory of the "Telescope Makers of Springfield," perched on the summit of a fir-clad mountain three miles from that community in southeastern Vermont. The illustration gives only a meager impression of the equipment available. At the right, just out of the photograph, is the tower of a spectrohelioscope to be constructed similar to the one described in Part IX. At the rear (south) is a polar Cassegrainian telescope of the type shown in Figure 42 at VII; also the Sun telescope shown in Figure 32. Inside there is a star transit, a well equipped optical shop, an equally well equipped kitchen, sleeping quarters and a collection of telescopes which may be taken outside for use. Inscribed on the facia of the roof, in front, is the verse, "The Heavens Declare the Glory of God."



RUSSELL W. PORTER

With one of the numerous sun dials he has made. From a photograph made and inserted by The Editor.

CHAPTER II.

Making the Mounting

Seated well up in the bleachers (Latitude 43 degrees N) we Vermont astronomers can command a fine view of the greatest of all spectacles—the solar system. In it, the race is always on. The entrants gain and lose on each other as they pass us by. Until Copernicus somewhat rudely shoved us over to one side we thought we saw the show at first from a central coign of vantage. However, the change was not all a loss, for it placed us on a movable platform where we became a real participant.

I always like to think of this old earth of ours as a gigantic piece of exquisite mechanism with which by the aid of a mirror of my own making, I am privileged to play at will. I pick it to pieces, watch it turn over and check up on its geometrical makeup. I then like to sense my exact place on this ball (for me this place is not quite halfway between the equator and pole), and,

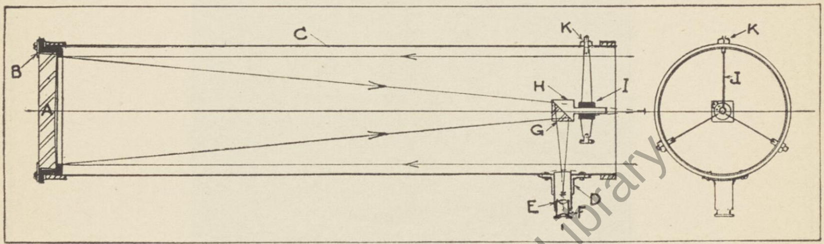


FIGURE 19

A TYPICAL NEWTONIAN MOUNTING—THE TUBE

It was Sir Isaac Newton who devised the method of using a small diagonal mirror to bring the rays to a conveniently located eyepiece. In place of such a mirror, an unsilvered diagonal prism costing only a few dollars, may be used to advantage.

from this vantage point as it swings around the sun, to watch our neighbor planets weaving their intricate paths through the stars. But before I may appreciate the beauties of this mechanism, my mirror, along with its prism and eyepiece, must be properly mounted.

The essentials of an efficient reflecting telescope mounting are: that the optical train, viz., mirror, prism and eyepiece, be held rigidly in relation to each other; that provision be made for conveniently adjusting these parts; and that the whole be supported on bearings that will allow any celestial object to be easily followed as it moves across the sky.

The first of these conditions is readily met by the use of a tube of sheet metal to which the different optical parts are attached. Since the hollow cylinder is one of the stiffest forms for its weight and can be obtained of any tinsmith in galvanized iron at moderate cost, the advantage of its use is obvious. The mirror A (Figure 19) rests in the cell B, fastened to one end of

the tube C. The eyepiece F, fits into another tube E, called the adapter, which slides easily in a flanged piece D fastened to the side of the telescope tube. The prism G (hypothenuse side) is held against a corresponding face on member H. A stud on the rear of H, fits in the sleeve I, which is held to the telescope tube by the three knife edges J. The knife edges have threaded ends, they rest in slotted holes in the tube and are provided with set nuts. With this arrangement the prism may be adjusted to bring it into proper relation to the mirror and eyepiece.

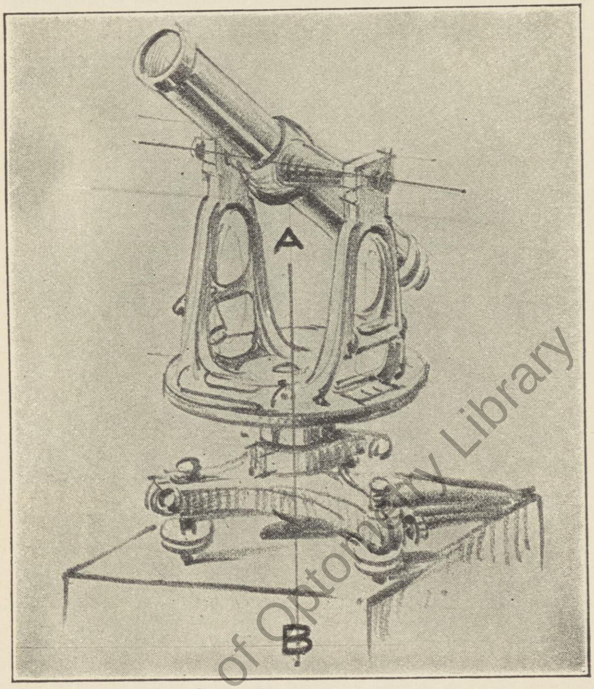


FIGURE 20

THE SURVEYOR'S TRANSIT

With its vertical axis, A-B, plumbed up, this type of mounting requires constant slow motion in two planes, in a series of steps, or zig-zags, in order that it may follow the stars.

This solution of our first and second essential conditions is the one now in almost universal use. The optical parts are easily removed without disturbing their adjustments when taken indoors for safe keeping. An additional refinement is a focusing rack and pinion. Sometimes a diagonal, flat piece of glass (silvered on its front surface) is substituted for the prism, but this is not

advised on account of there being added thus an unnecessary silvered surface which has to be protected. The prism, on the other hand, is not silvered and is totally reflecting, owing to the acute angle at which the light meets its hypothenuse side.

The tube must now be so supported as to follow the stars. Of the several ways this may be accomplished, one condition underlies them all—there must

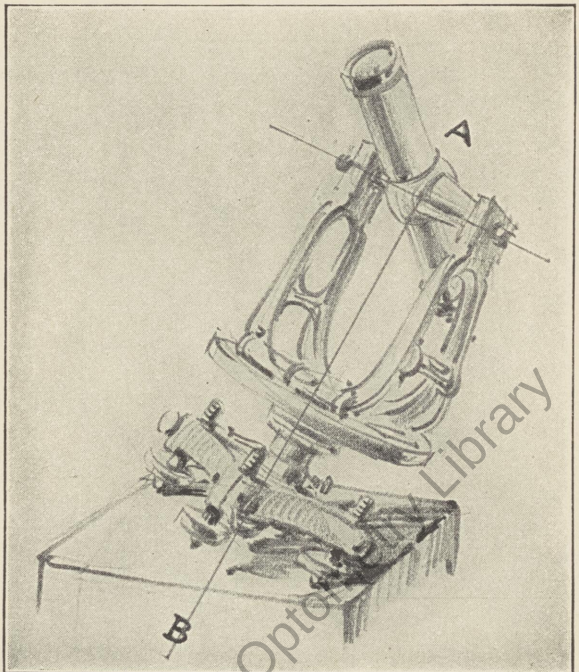


FIGURE 21

THE EQUATORIAL MOUNTING

The transit of Fig. 20 has now been tilted until its axis, A-B, is parallel to the earth's axis. It will now require slow motion in only one direction instead of two. Fig. 22 explains the theory of this change.

be provided two bearings at right angles to each other and one of them must be capable of being adjusted parallel to the axis of our earth. A familiar instrument having these two bearings at right angles to each other is the surveyor's transit or theodolite. One of the axes, A-B (Figure 20), is always plumb. Imagine the instrument tipped over until this axis is parallel to that

of the earth (Figure 21), and we have what astromoners call an equatorial mounting. The axis about which the telescope swings is called the declination axis.

To visualize this condition of parallelism between the polar axis of the mounting and the axis about which the earth rotates, I have drawn Figure 22. In this schematic diagram a mounting is shown placed on the earth's surface in about the middle latitude of the northern hemisphere. Its polar axis

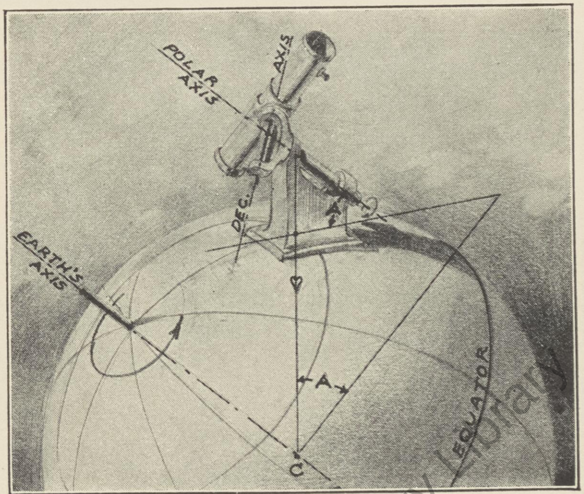


FIGURE 22

THE "WHY" OF THE EQUATORIAL MOUNTING

First, in any equatorial telescope, the angle A, between the polar axis and the northern horizon, must equal the observer's latitude. Once adjusted thus, it need never be touched—unless the telescope is moved to another latitude. The polar axis is now parallel to the earth's axis, and although these are several thousand miles apart, this makes no appreciable difference in observing objects millions of times as far away. Having now eliminated this factor, any star may be followed by slowly revolving the declination axis and telescope tube as a whole around the polar axis. Whether we now choose to point the tube high or low in the skies makes no difference—wherever it is, its polar axis is always performing the necessary slow motion to offset the earth's daily rotation.

and the earth's axis are seen to be parallel to each other. At right angles to the polar axis is the declination axis about which the tube swings, allowing it to be pointed at any angle with the observer's horizon.

The earth, turning in the direction of the arrow, gives the stars an apparent motion in the heavens in the opposite direction, and a slow motion of the polar axis spindle of just the right amount will keep any star (regard-

less of its elevation above the horizon) constantly in view in the eyepiece of the instrument. When the telescope is pointed toward the pole of the heavens, stars move across the field of view slowly. Polaris, for example, seems hardly to move during an entire evening.

But as the tube is now swung down toward the celestial equator, the apparent motion of the stars is accelerated. Thus, the motion of the moon in a high powered eyepiece is so rapid as to give an almost overwhelming realization that the earth is turning over in space. Were the mounting to

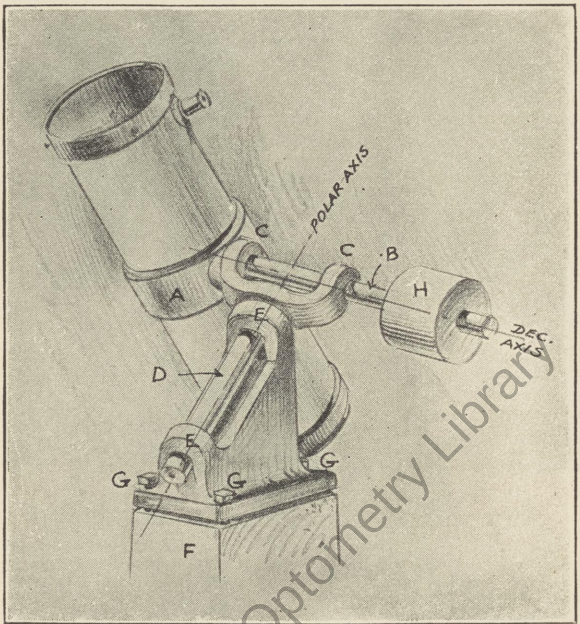


FIGURE 23

THE GERMAN TYPE OF MOUNTING

This is the commonest of the equatorial types. It has many advantages and comparatively few drawbacks.

be erected at the earth's poles, the polar axis would, of course, be *vertical* to the observer's horizon; if placed anywhere on the earth's equator it would be *horizontal,* or parallel to one's horizon. However, the great bulk of us humans live somewhere about midway between these two extremes, and in any case the polar axis of one's mounting makes an angle A with his northern horizon equal to his latitude, for the two angles A, A, are always the same, as is evident from the two triangles shown.

Of the several types of mountings the most common type is known as the German mounting. (Figure 23.) The tube fits into a ring A, to which is attached a spindle B. The bearings C, C, for this spindle are at one end of spindle D, and D's bearings, E, E, are part of the casting fastened to the pier F. When D is adjusted by the screws G, parallel to the earth's axis, any object in the telescope eyepiece will be held in the center of the

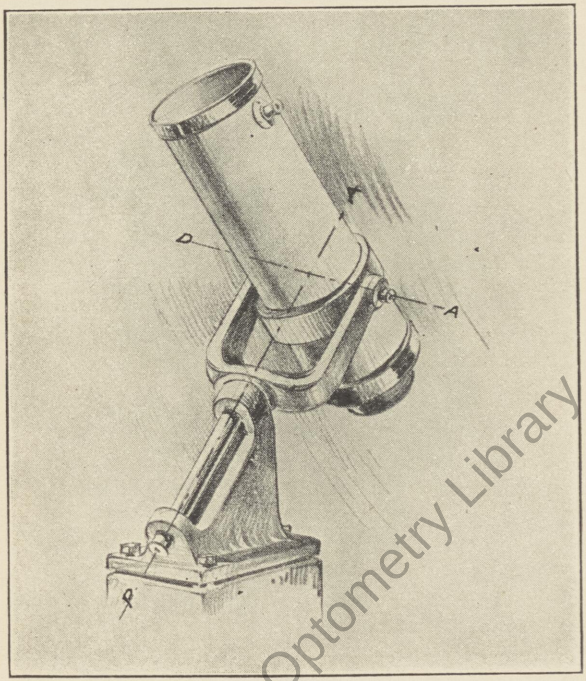


FIGURE 24

THE ENGLISH, OR FORK TYPE

It dispenses with counterweights, but it is not as rigid as some others, due to its long overhang over the bearing. P-A is the polar axis, D-A is the declination axis.

field by revolving the instrument about D just fast enough to counteract the diurnal rotation of the earth.

This type of instrument is completely counterbalanced, and the tube is gripped at such a point that it will remain pointing in any position without clamping. Since it overhangs one side of the polar axis, sufficient weight H, is added to the opposite end of the declination spindle in order to bring the center of weight into the polar axis near its upper bearing. The total

weight is, therefore, inside the base and is equipoised. Usually, for convenience in following a star, a worm and worm wheel are provided on the polar spindle.

In the English or fork type, Figure 24, the tube is swung in a yoke attached to the upper end of the polar spindle but considerably overhanging

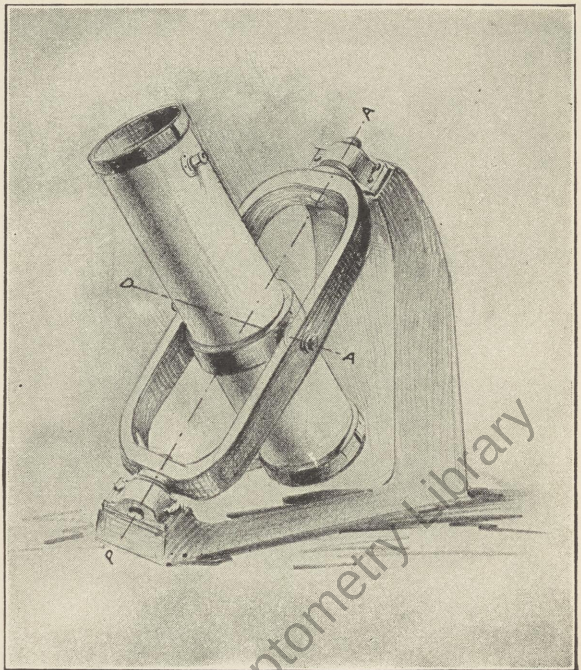


FIGURE 25

THE DOUBLE YOKE TYPE

Compare this with Fig. 24. Being included within two bearings, the tube is very stable. There are no counterweights. Part of the northern heavens is, however, inaccessible. The famous Hooker telescope at the Mt. Wilson Observatory, near Pasadena, California, with a 100-inch mirror, has this type of mounting.

the pier. This type has the advantage of requiring no additional counterweights.

This excessive overhang of the tube in the fork form just described is overcome in a third type where the tube is brought within the two bearings of the polar axis, whose spindle is enlarged into a double yoke, within which the telescope swings in declination, Figure 25.

However, all forms of mountings are compromises, and in the last-named type, the gain in rigidity is obtained at the cost of cutting off from view a part of the northern heaven. It is interesting here to note that this was the form of mounting which was adopted to carry our greatest of all mirrors—the 100-inch reflecting telescope at Mount Wilson, California.

Still another form is obtained by expanding the upper bearing of the

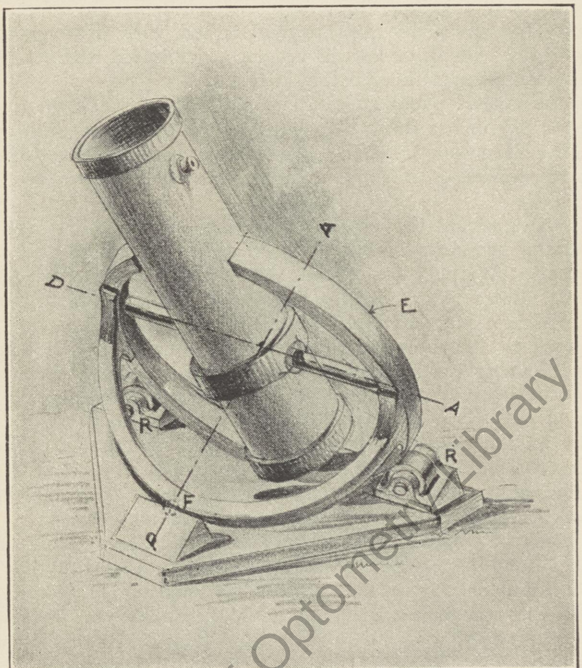


FIGURE 26

THE EQUATORIAL RING TYPE

The ring revolves on rollers, R, R. The polar axis is P-A, and the ring rolls in a plane parallel to the earth's equator. This type is especially steady.

polar axis to a large equatorial ring E, Figure 26, within which the telescope swings on its declination axis, the lower end of the polar axis having a thrust bearing at F. The large ring turns on the two rolls R, R. This type of mounting is very stable, the center of weight of the moving parts being well within the supporting rolls and thrust bearing. Part of the equatorial ring E, is cut away in order to allow the tube to reach all parts of the heavens.

In all of these mountings considerable machining of parts is required, as well as special castings running into a lot of money, thus putting them beyond the means and capabilities of most amateurs. The *Springfield Telescope Makers* selected the first of the types just described, the German form. But they had access to the resources of the machine shops here and were all skilled mechanics. I shall, therefore, at risk of possible criticism, describe a wooden equatorial mounting containing the essential features, but which may be very easily put together from materials available anywhere. When the mirror maker has given his glass a good tryout with this mounting he will either be satisfied with it, or he will become so enthused with its performance, that he will attempt something better in metal.

To hold the optical parts a clear, straight-grained plank of pine or spruce A, Figure 27, $1\frac{1}{2}$ inches thick, 6 inches wide at the mirror end and tapering to 2 inches at the other, is used. The mirror rests in a one-inch board $6\frac{1}{2}$ inches square screwed to A as shown and recessed for the mirror to a depth of one-half inch.

In order to forestall the possibility of the mirror falling out of its cell, wooden buttons or brass clips may be distributed around the edge of the recessed board. At the back of this shelf there are three adjusting screws on which the mirror rests. At the other end of A a hole is bored to take the tube C. C is a piece of brass tubing about 6 inches long, with an inside diameter equal to the diameter of the eyepiece to be used. One end of C is cut down, leaving two ears at I, with enough spring in them to grip and hold the one-inch, totally-reflecting prism. Some of the tube between the plank and prism is cut away in order to offer no more obstruction to incident light on the mirror than is necessary to support the prism. The other end of the tube is slotted in order to allow the eyepiece to slide for focusing. So much for the member holding the optical parts. When assembled, find the point on A where it balances and bore a $\frac{1}{2}$-inch hole.

D is a block of wood 6 inches square, and $2\frac{1}{4}$ inches thick. Part of one side, within a four-inch circle, is recessed $\frac{1}{8}$-inch. Unfortunately this circle was not indicated on Figure 27. Two holes, respectively $\frac{1}{2}$-inch and 1-inch in diameter, are now bored through the block as shown. When finished it is attached to A, using a $\frac{1}{2}$-inch bolt 4 inches long provided with washers and a butterfly nut.

The polar axis is a piece of one-inch shafting about 2 feet long. Have the blacksmith bend over 6 inches of it until it makes an angle with the rest of the shaft about equal to the complement of the observer's latitude.

The remainder of the mount consists of a 2-inch steam pipe, 2 feet long, cast vertically into a concrete pier. When the bent end is adjusted parallel to the earth's axis by lining it up on Polaris some evening, cement is poured into the steam pipe, and allowed to set, the block D is dropped down over the shafting in the hole provided for it, and the mount is finished.

The butterfly nut will give the desired pressure between A and D so that the telescope will turn, and will remain fixed at any required declination. If D is slotted as shown, the wood screw M, will take up any looseness of the bearing of the polar axis. The mirror is adjusted in its cell until

its optical axis passes through the center of the prism (see J, Figure 27). The adjustment is tested by placing the eye well behind the prism and noting whether the reflection of the prism is in the center of the mirror. Should it be found, say, at K, unscrewing the screw L, will make the reflection move toward the center.

The prism is adjusted by taking out the lenses of the eyepiece and looking

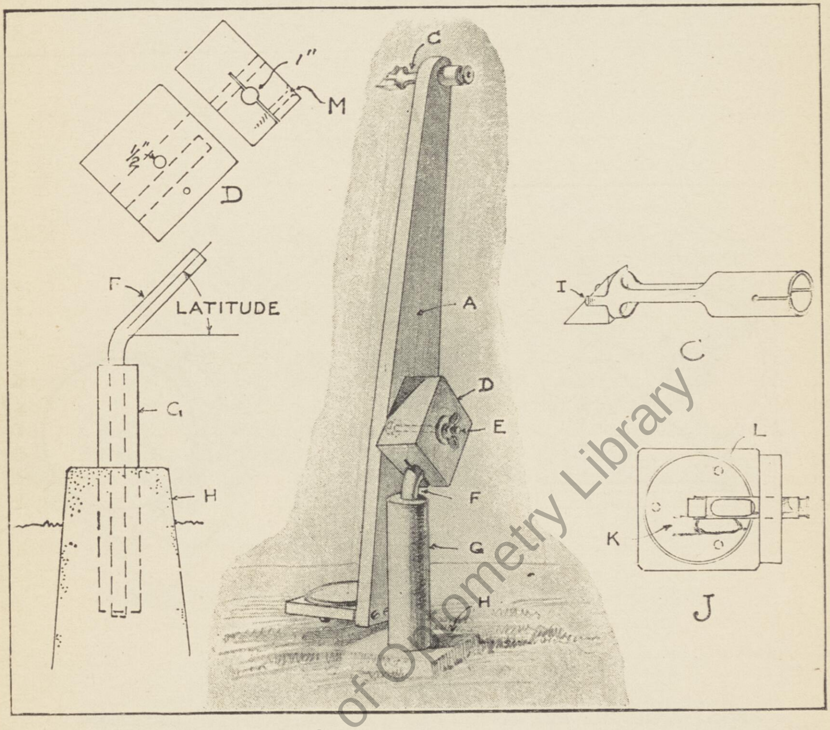


FIGURE 27

A WOODEN, EQUATORIAL MOUNTING THAT ANYONE CAN MAKE

Although it is inexpensive and simple, the amateur who lacks access to machine tools will find this a very serviceable mounting. If care is used in bending the shafting F properly, and setting it approximately parallel to the earth's axis, the telescope will need to be moved in only one plane in order to follow a star for considerable periods of time.

into the adapter. The reflection of the mirror will be seen in the prism. The reflection of the prism should be central and must be made so by filing the seat of the prism. A slight movement of the prism between its ears will

cause the reflection of the mirror to move and this will indicate where the seat should be altered.

The focal length of the mirror has previously been found during the knife-edge tests. It is one-half its radius of curvature. The distance from the surface of the mirror to the center of the adapter tube will therefore be this focal length less the distance (about 5 inches) from the center of the prism to the focus of the eyepiece. From mirror to adapter would be $48 - 5 = 43$ inches for a glass of four feet focal length. The focal plane of

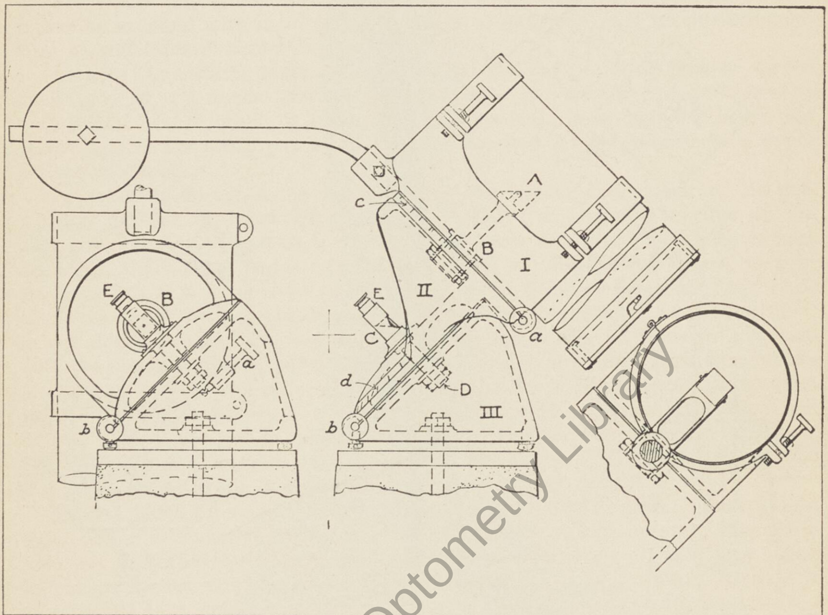


FIGURE 28

FRONT AND SIDE ELEVATIONS OF THE SPRINGFIELD MOUNTING

*This is the mounting shown in Figs. 30 and 31. (This type was originated by Porter.—*ED.)

a negative eyepiece is somewhere between its component lenses; of a positive eyepiece it is just in front of the field lens.

It will be observed that for zenith stars (objects overhead) the eyepiece will be found about at the height of the eye when standing. For objects at a lower altitude a chair or stool will be found convenient. The wooden part of the mount should be well painted and the polar axis should be kept slushed with hard grease. The wooden member can be lifted off the polar axis and taken indoors as a whole, for it is quite light. A cap of

some sort (a piece of window glass will do) should always cover the mirror when not in use, in order to preserve the lustre of the silvered surface.

One of the most convenient of equatorial mountings (Figures 28, 30, 31), and the one producing the most satisfactory results here at Springfield, Vermont, has the advantage of a fixed eyepiece. It is true a second prism is required, but this permits the observer to sit in one position for all celestial objects, looking comfortably down the polar axis. The two controls in right ascension and declination are within easy reach (Figure 30), the setting circles are large and need no verniers. The tube is counter-

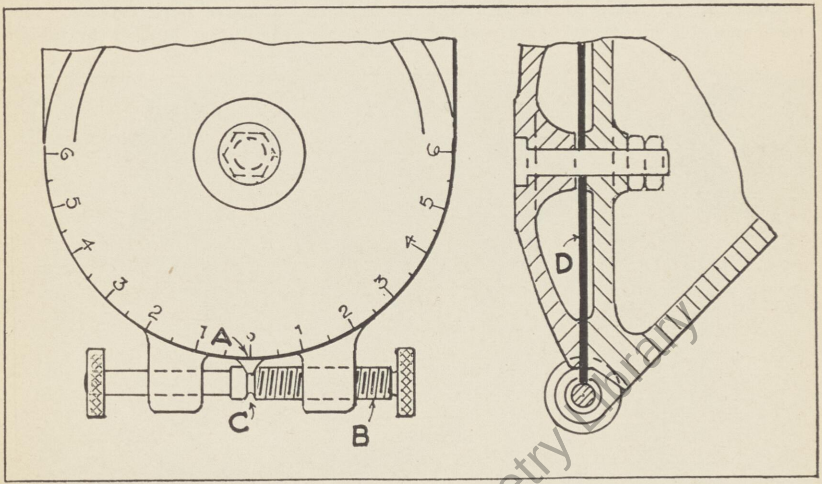


FIGURE 29

DETAIL OF THE SLOW MOTION, SPRINGFIELD MOUNTING

Front and side elevations. This is a part of Figure 28

poised and can reach all parts of the heavens. Loss of light, due to the addition of an extra reflection, is negligible.

Light from the mirror, after reflection from the usual prism A, in the tube (Figure 28) passes through the hollow declination stud B, to another prism C, directly over the polar axis stud D, and below the eyepiece. In addition to its fixed eyepiece, a distinctive feature of this mounting is the manner in which the two axes are maintained. Instead of two spindles held in bearings at their extremities the bearing surfaces consist of large areas held together with small central studs, that of the declination axis being hollow. This arrangement permits very rigid forms of the three castings I, II, and III. The setting circles c and d are cut on member II in convenient positions for reading.

Control in motion is as follows: The two tangent screws a and b,

(Figure 28) bear against spurs on the edges of two thin sheet steel disks inserted between castings I, II and III. Figure 29 shows the detail of the slow motion about the polar axis. The spur A, on the periphery of disk D, bears in the circular groove C, of screw B. Sufficient friction is maintained between the bearing surfaces of the disks so that not only will the tangent screws produce slow motion on either axis, but will also allow the telescope to be swung quickly through large arcs of the heaven in both declination and right ascension. This arrangement makes a very good substitute for the expensive worm wheel drives.

Of the many designs of mountings which enable the observer to sit in comfort in an enclosed and warmed room, lack of space here forbids. The most notable of these among amateurs is the Hartness Turret, in which

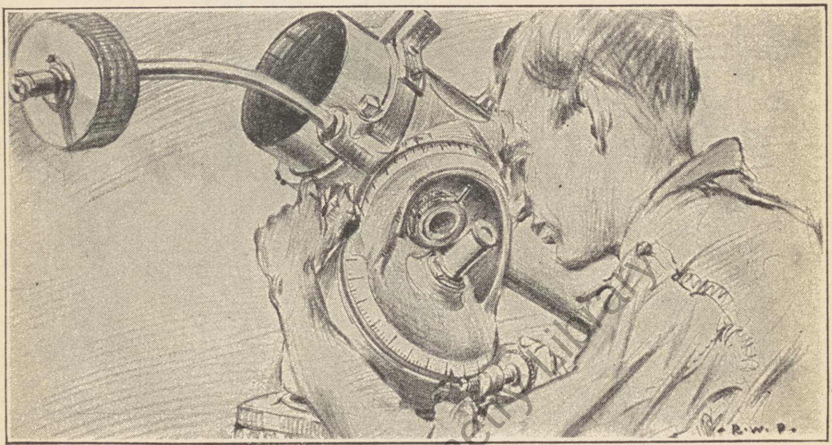


FIGURE 30

THE SPRINGFIELD MOUNTING, WITH DETAIL OF SETTING CIRCLES

Everything is within easy reach and vision. Note the slow motion screws for following the stars. This mounting may be made by a machinist, from blueprints.

the roof of the building, made of cast iron, and rotating on rolls, carries the optical parts and delivers the light from a 10-inch objective to an eyepiece inside the room. Bell, in his book, *The Telescope,* describes several of these instruments.

Of reflecting telescopes, apart from their mountings, mention has only been made here of the Newtonian reflecting type. There are, however, others, but they are not as practicable for the amateur as the Newtonian.

In the Gregorian, a small concave mirror just outside the focus, reflecting the light from the mirror to a secondary focus behind the mirror through a central hole in the glass, is substituted for the prism. The Cassegrainian is similar, but it interposes a convex mirror just inside the focus. Both of these

combinations greatly increase the virtual focal length of the mirror without increasing the length of the tube, but they are useless for day work on

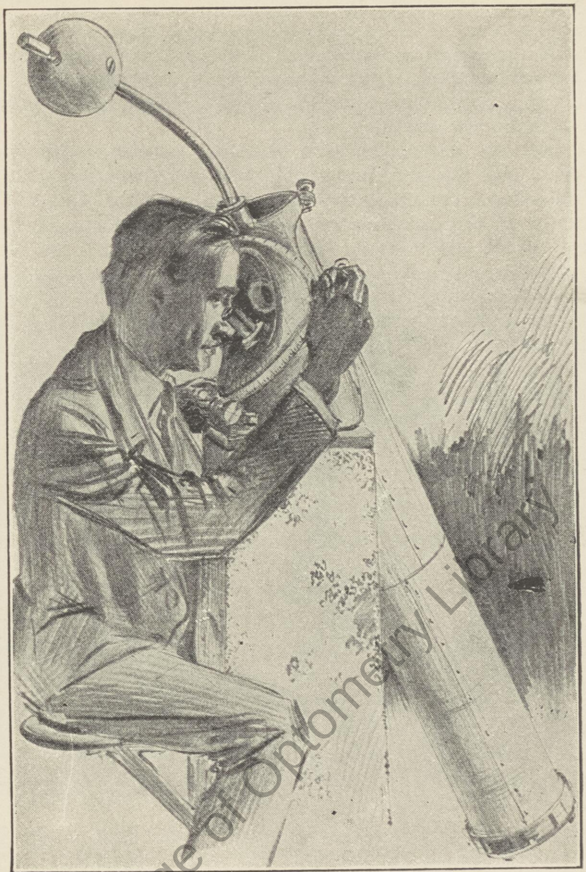


FIGURE 31

THE SPRINGFIELD EQUATORIAL MOUNTING

The observer's position is fixed and comfortable. The light from stars in any part of the heavens reaches his eye via two prisms. Thus, instead of being forced to assume many uncomfortable observing positions, the astronomer is always looking down, as if he were using a microscope.

terrestrial objects, and they require the figuring of an additional optical surface.

With an equatorial mounting provided with setting circles, the astronomer can select any celestial object (above the horizon) by looking it up in the Nautical Almanac and setting the circles to the correct declination and hour angle. He also sets his watch running on star time. If he has made no blunder in his calculations, and if his instrument is in fair adjustment, the object will appear in the field of view of the eyepiece. It may be an obscure double star, or a nebula, or a cluster, or a comet, wholly invisible to the naked eye and impossible of finding in any other way.

Thus is seen the desirability of a mounting provided with circles if one wishes to delve into the great storehouse of hidden wonders above us.

On the other hand, the simple wooden mounting I have described will enable one to pick up all the apparent celestial bodies—the moon, the planets, sun spots, bright double and multiple stars, two nebulae which are visible to the naked eye and one or two star clusters.

Care must be taken in observing the sun, for the mirror makes a powerful burning glass. It works best for this purpose while unsilvered, but if it is already silvered, cover the glass with a cardboard in which an inch hole has been cut. The safest way is not to use the eye at the eyepiece but to project the sun's image on a card placed outside the eyepiece.

It is hoped that the amateurs will not copy these mountings slavishly, and partly for this reason, set dimensions are not given except in a few instances. When controlled by a clear comprehension of the principles of the mountings used and some mechanical judgment, the exercise of the amateur's individuality in planning his telescope is highly desirable. For example, Mr. Ions, formerly of Texas, has built a very ingenious equatorial mounting almost entirely from discarded parts of a Ford car.

The above suggestion regarding the exercise of some degree of individuality will, it is hoped, obviate the production of a large number of telescopes, as like as a lot of peas.

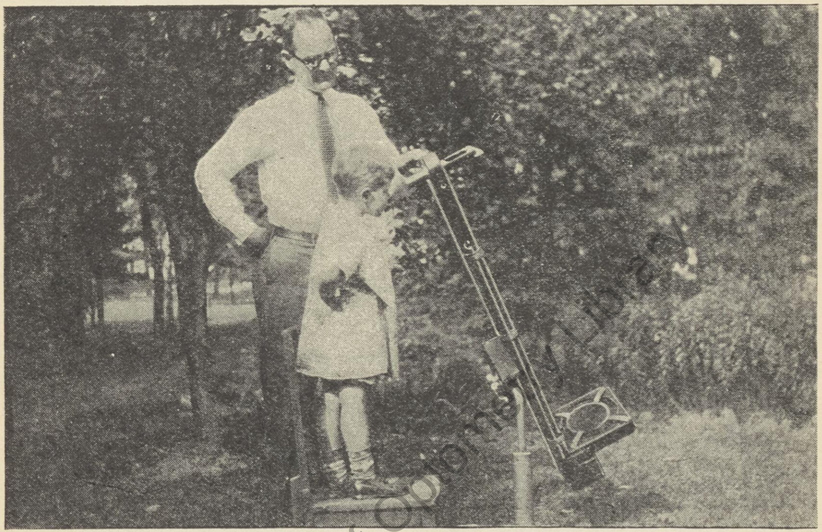
Eyepieces

Eyepieces or oculars for astronomical telescopes are usually the Hyghenian, set in 1¼ inch tubes. Their powers vary according to their equivalent focal length *(e. f. l.)*. For our telescope of 4-foot focal length an eyepiece of 1-inch *e. f. l.* would give 48 magnifications (the focal length of the mirror divided by the equivalent focal length of the eyepiece, gives the total magnification). A ½-inch eyepiece would give 96 magnifications, and a ¼-inch 192, respectively. This makes a good battery of eyepieces for range of powers. They cost from about six to ten dollars apiece. It is not advised to use a higher power than ¼-inch *e. f. l.* as the atmospheric disturbances and the quality of the mirror surface set a practical limit to the degree of magnification.

Were I to have but one eyepiece at first it would be the lower power, viz., 1-inch *e. f. l.* The Hyghenian eyepiece is not, however, achromatic, and the color is quite noticeable in a mirror telescope. I have used almost exclusively, the Hastings three-lens, positive oculars, as giving a beautiful, flat and colorless field.

Eyepieces from old microscopes are not to be despised and they work very well with a mirror. They are usually of low power and are useful for terrestrial observation.

A finder is a small telescope fastened to the eyepiece end of the telescope as an aid in pointing the tube to any desired and visible object, and it is undoubtedly a convenience in picking up a star quickly, although we usually get along here in Springfield by sighting along the tube itself. Of course, with one's mounting provided with setting circles in good adjustment, a finder is unnecessary.



A HOME MADE TELESCOPE

This is the type described on page 28 and 29, except that the wooden support for the mirror has three concentric circular depressions—a six-inch in the bottom of a seven-inch, and a seven-inch in the bottom of an eight-inch. This allows for two larger sizes of practice mirrors. At extreme bottom is a battery box and a wire leads along the upright to a countersunk, miniature electric lamp which may be turned on for use when consulting star maps, etc., simply by screwing in the bulb. Described in the Scientific American, March, 1927, page 195.

CHAPTER III.

A Sun Telescope of 100-Foot Focal Length

This is not as ambitious as it sounds. The only optical parts needed are two 6-inch mirrors, one of them concave, the other flat.

The arrangement is shown in Figure 32, which requires little explanation. The fixed mirror is placed on the southern side of the house, opposite the room into which the sun's image is to be thrown, and distant from the window a few feet less than its focal length.

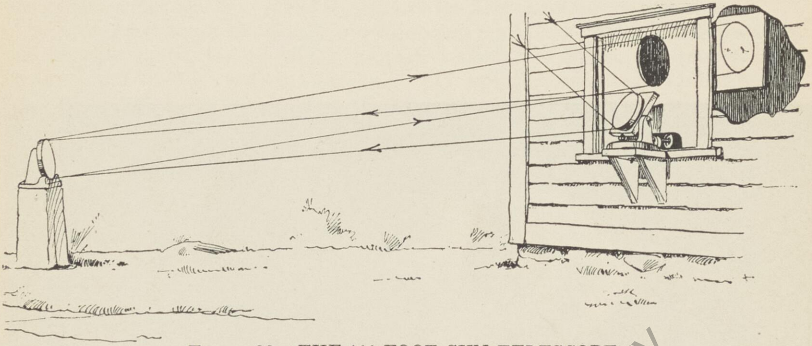


FIGURE 32. THE 100-FOOT SUN TELESCOPE.

The flat mirror is placed on a shelf on the windowsill and is manipulated from indoors in such a way as to catch the sun's rays and project them to the concave mirror in the yard. Using a 6-inch mirror, the image of the sun, as thrown on a screen inside the house, will actually be larger than the mirror itself. It will be bright and strong.

The screen may be a square of white cardboard on which the sun's disk will show up to good advantage, displaying the spots, etc.

Such a sun telescope, with a pair of 16-inch mirrors, was set up at *Stellar Fane,* near Springfield, Vermont, and was described in the November, 1925, *Scientific American.* We removed the entire window sash and substituted a shutter of beaver board having a hole just large enough to let in the sun's image. Our 16-inch concave mirror (of 75-foot focal length) had, however, to be diaphragmed down to only four inches effective diameter.

In order to show the detail more closely, the scale of Figure 32 was purposely distorted. The two axes of the flat and the method of controlling them in order to offset the sun's motion are shown in the diagram. The mirror rests on a wooden block which can be tilted about a horizontal axis, and the whole is capable of being rotated around a vertical axis consisting of a stud which projects upwards from the shelf. The whole apparatus thus constitutes an alt-azimuth mounting, similar in principle to that shown in Figure 20.

With this sun telescope a whole roomful of people can study the sun spots, which show with considerable detail.

In testing a flat surface, which may be done at the center of curvature of a spherical mirror (see Figure 33), it is manifest that if a spheroid *appears* flat with the knife-edge at its center of curvature, the introduction of a perfect plane surface at A will not alter the appearance of the spheroid, which is now seen as if it were placed at B. Therefore, any departure from a flat surface will produce raised or depressed areas superposed over the apparent flatness of the sphere. These must be removed by figuring, just as though you were working on the spherical surface alone, as explained in Chapter I.

Thus, to determine whether the flat is concave or convex, locate the position of the knife-edge as it comes in from the side, where the shadow darkens uniformly (as in testing a spheroidal mirror). Then test with the knife-edge coming down from above. If it lengthens the radius of curvature the flat is concave. If it shortens the radius it is convex. This effect is due to foreshortening, the flat being at an angle of 45° to the axis.

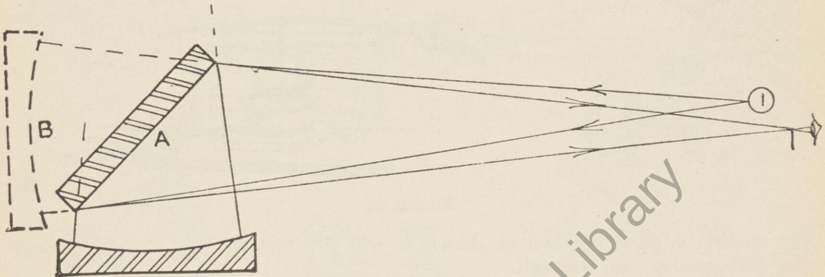


FIGURE 33. FIGURING A "FLAT" WITH A SPHEROIDAL MIRROR.

If the second arrangement of Figure 17 is used for testing, the hole in the flat should be made after the figuring. With ordinary commercial plate glass, this will result in a slightly turned-up edge around the edge of the hole, like the rim around a crater (due to strains in the glass). However, this distortion extends to so short a distance from the hole that it need not trouble the amateur in parabolizing.

A better way to produce an annular flat is to cut out the central portion first and cement the core of glass back into its hole again with plaster of paris. The glass is then fine ground, polished and figured to a flat as one surface, and the core is afterward knocked out.

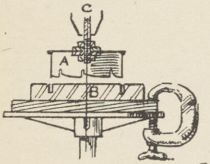
The concave mirror has too great a focal length to be tested with the knife-edge, for the shadows would be altogether more subtle, even, than those of the long focus paraboloid whose shadowgraph is shown in Chapter I. The mirror will therefore be fine ground for only a few moments (using, for convenience, the back of the flat as a tool) until the thinnest of tissue paper can be inserted between its surface and a straight-edge. It is then polished, taking great care to maintain good contact. Let us hope it is close to a spherical surface.

CHAPTER IV.

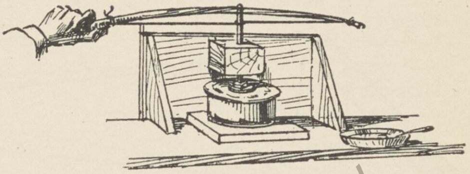
Wrinkles

Here is a way to cut out a circular disk of glass from a slab. Assuming that we have access to a drill press, we proceed as follows: A cutter is made by fastening a tin can to a bolt, as shown in I, Figure 34. The can *A* is cut down, leaving walls about twice as long as the thickness of the glass to be cut. A hole large enough to take the bolt is punched through the back of the can, washers and nuts are added loosely. The bolt end is then inserted in the chuck *C* of the drill press. Shift the can on the washers until it runs smoothly, then screw the nuts home.

The glass slab *B* is pitched to the board and clamped to the table. Carborundum (about No. 200) and water are fed under the cutter, and in about half an hour the slab will be cut through. The cutting edge of the can, though not perfectly circular, will, however, cut out a perfect cylinder from the glass. If



I



II

FIGURE 34

the cutting edge is notched as shown, it will cut faster. The drawing shows the slab nearly cut through.

The old fashioned bow drill (II) will cut small disks if a drill press is not available. The set-up required needs no explanation. Of course the bolt must be longer than the one used with the press.

"Sleeks" is a term applied by glass workers when for some unknown reason a number of very fine scratches appear on a glass surface during the polishing. They are so fine as to be indistinguishable unless the glass is held up to the light and its surface viewed by reflection. It is said by English opticians that if the pitch lap is thoroughly dried, a few moments of vigorous dry polishing will remove them. My experience has been that they appear only during the last stage of figuring.

It is always desirable that the walls of the telescope tube reflect no light into the eyepiece. In refractors this is prevented by placing diaphragms along the inner wall of the tube at certain intervals. Turpentine added to ordinary black paint gives a good dull surface; coach black, used for blackening the interiors of cameras and other optical instruments, is the best of all. Brass tubing may be given a permanent dull black surface by thoroughly cleaning the tube and immersing it in a saturated solution of nitrate of copper. Pieces of copper are dissolved in nitric acid until it will take up no more. The

tubing is hung on a bent wire, immersed and held in an alcohol or gas flame until the darkening brass assumes an even shade.

A diagonal such as is used on the Springfield Mounting may be assembled from the parts shown in III, Figure 35. The two pieces *a* and *b* are cut out with a hack saw from a sheet of brass one-sixteenth inch thick. Piece *b* is bent along the line *AA* to a right angle and the two holes are then drilled out and filed smooth. The short section of tubing *B* is to fit the eyepiece, and the longer tube *E* the adapter, and the two holes are made correspondingly, but a little smaller in diameter. The back plate *a* is then screwed to *b*, using the smallest brass machine screws obtainable; the ears *DD* are bent up to prevent the prism from falling out. The prism should fit fairly loosely. Shim up

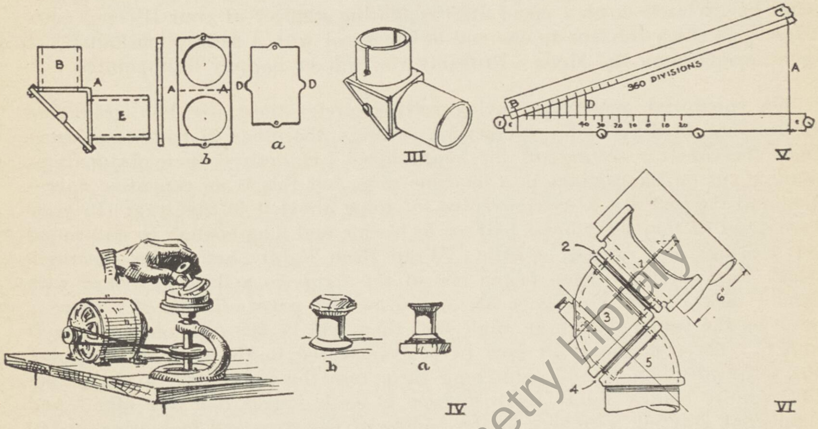


FIGURE 35.

with paper on the hypothenuse side until there is no shake. After the prism has been fitted, remove it, screw on the plate again and solder on the two tubes.

If a revolving spindle can be found or rigged up, a small double or plano-convex lens is not a difficult thing to make, especially in this mechanical age with small electric motors in such universal use. The end of the motor's armature shaft itself will do on a pinch, but it is easier to belt off to a vertical spindle. Even the bow drill can be resorted to if necessary. Of course the calculation of the curves of lenses and the kinds of glass to be used in making a telescope objective are beyond the purpose of this chapter, but a simple magnifying glass of, say, an inch in diameter can easily be made.

With a tin can about an inch in diameter, cut a disk from a piece of broken wind shield or looking glass, as previously described. Pitch the disk to a small piece of wood, such as a spool, for a handle, as in IV, *a*. Grind down the edge

on a piece of glass or iron until it is roughly convex, like *b* in the figure. Cut out another disk of the same size and pitch it to the spindle. Turn on the motor just before the pitch becomes hard, and with the thumb and forefinger steady the disk until it runs concentric with the spindle.

Start grinding the roughed out disk on the glass tool, using the same grades of carborundum as in mirror making. Give the spool a rocking motion, very much like that of a spinning top before it is going to fall. Very soon the lens will take on a smooth, curved surface, and a cup-shaped depression will begin to form at the center of the tool. By the time this cavity has reached the edge of the tool the curve of the lens will have flattened considerably. Bring the glass to a fine-ground surface (it will surprise you to see how quickly it is done, in contrast to hand work), clean the tool, spread on a sheet of honeycomb foundation and polish. The polish should be complete in about 15 minutes. Whittle down a spool until it fits the adapter of your silvered glass telescope. Stick the lens to one end of the spool with a little pitch and try it as an eyepiece on the Moon. Probably you will be happily disappointed.

On equatorial mountings having setting circles there are two graduated circles—one in degrees for declination settings, the other in hours and fractions thereof—for setting off the hour angles. If desired these graduations may be cut on the castings in a machine shop, but this is an expensive operation and the cost can be circumvented by going about it in this way: Prepare two strips of thin sheet brass half an inch wide and long enough to go around the castings and overlap a little. Wrap them tightly and make a scratch where they overlap. Then fasten one of the strips to a drawing board with thumb tacks, as in V, Figure 35, and draw the perpendicular *A*. Place a scale on the board at such an angle that there will be 360 divisions between *B* and *C*. These divisions are now to be transferred to the strip by dropping the perpendiculars *D* and scratching them into the brass with a sharp tool like a knife blade. Every tenth division is made longer than the others and numbered, starting with zero at the middle of the strip and increasing to 180 either way. This is the declination circle.

The strip for the hour circle is similarly treated, except that here there are but 144 divisions divided up into 24 hour divisions, each hour subdivided six times, giving a least count of 10 minutes of time.

The precision obtainable by making the circles by hand in this manner is enough for setting purposes, for all that is needed is an accuracy sufficient to bring any star desired well into the view of a low power eyepiece.

Pipe connections have been used in building equatorial mountings. I would offer as a suggestion the availability of the large 6-inch connections shown in VI, Figure 35, as a substitute for the rather expensive castings of the Springfield mountings. They would comprise the "T" (1), close nipple (2), 90-degree elbow (3), close nipple (4) and 45-degree elbow (5). These parts ought to move very smoothly on the threaded nipples, since the threads themselves are tapered and can be screwed together until they bear freely on each other without any shake.

One way of making a stand suitable for the coelostat of the sun telescope described in Chapter III, is indicated below. One stand, made of wood, is shown at I, Figure 36, and another, of metal, at II. The board holding the flat mirror is hinged at *A* to another board *B*, with a stud passing through it into the bracket shelf below. With hard grease between board *B* and the

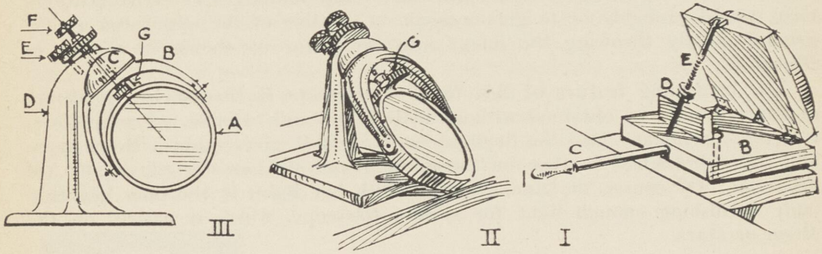


FIGURE 36

shelf below, the handle *C* will turn the mirror in azimuth and the nut *D* on the threaded rod *E* will raise and lower the mirror.

This last is not, however, so good as the equatorial mounting shown at II in perspective, and in section in III. The mirror cell *A* is swung in the inverted fork *B*. The hollow spindle *C* of the fork passes through the standard *D*. Motion in right ascension is transmitted through pinion *E*, and in declination through pinion *F* which engages a short section of a curved rack *G* fastened to the side of the cell.

The best time for viewing the Sun's image is early in the morning before the air has become badly disturbed by convection currents, or on sudden clearing after a cloudy day. The Sun's image will be about 10 inches in diameter and just bright enough to be viewed comfortably with the naked eye. It is surprising how rapidly the image moves across the screen, and it

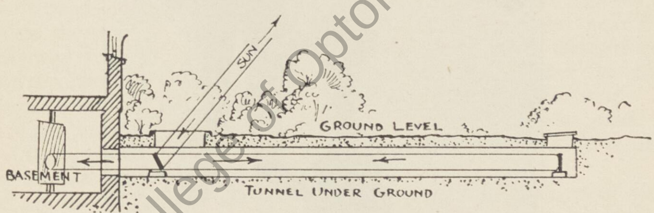


FIGURE 37

is interesting in this connection to note that we have here a brilliant image twice the diameter of the mirror that produced it. This shows forcibly that the diameter of the glass has nothing whatever to do with the magnification—the size of the image is a function of the mirror's focal length, only.

It is probable that the steadiness of the image would be markedly improved if the Sun's rays between the two mirrors passed, say, through or under foliage or trees. The air in the shade of vegetation is much less disturbed than air over exposed earth or rocks. At "Stellafane," near Springfield, Vermont, the Sun Room is upstairs and we think much of the unsteadiness is due to the heat rising along the southern wall of the building. The best arrangement would probably be to get as much as possible of the apparatus underground, finally throwing the image into the cellar as shown in section in Figure 37.

The intriguing feature of this form of telescope is that such a powerful instrument may be obtained with so little labor and expense. Furthermore, it brings astronomy into the daylight hours, and it gives quite a thrill to be able after breakfast to turn on the mirrors and see how the Sun spots are behaving. Of course the Sun, prodigal with her light, is the only heavenly body furnishing enough light for such a telescope, which is useless on the Moon or stars.

A HOME MADE TELESCOPE

Described in Scientific American, October, 1927, page 377. Made by Lieutenant Colonel W. P. Moffet, U.S.A., who stated that the entire cost was just under fifty dollars.

CHAPTER V.

Adjustments

The following instructions for adjusting the optical parts of a silvered glass telescope apply to any one of the mountings already described—in fact, to any reflecting telescope of the Newtonian form. If the three optical parts are not in correct relation to each other, a star's image will have a flare or tail to it, and no matter how carefully one focuses his eyepiece, he will be unable to get fine detail on whatever he is studying.

Remove the lenses from the eyepiece and insert what is left of it in the adapter tube. If the eye is brought close up to the hole in the eye cap of the eyepiece, one sees (Figure 38, I) first, the walls of the adapter tube *B*, next (by reflection through the prism) the mirror *C* in its cell.

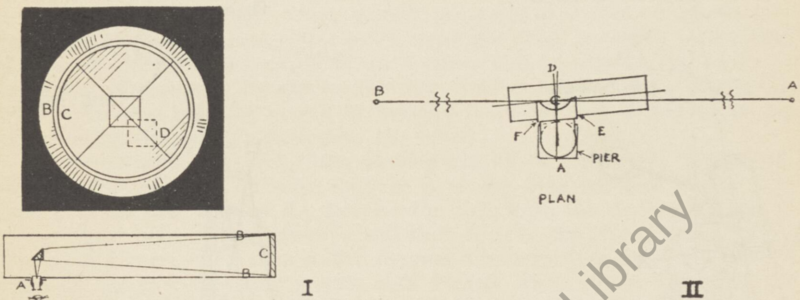


FIGURE 38

In the mirror will be seen a reflection of the prism itself, and if the mirror is in adjustment the prism will appear exactly at the center of the mirror where the threads temporarily stretched over the mirror cross. If the image of the prism shows at *D*, for example, then the side of the mirror near *D* must be moved away from the prism itself until the prism image is brought central. If the mirror itself is not seen centrally placed in the adapter the prism is out of adjustment and must be moved until *A* and *B* are concentric.

If a star's image is round and sharp, the adjustments are good, but if there is a flare, then the side of the mirror toward which the flare is pointing should be moved away from the prism.

These are the simple yet efficient means of adjusting the optical parts of the telescope. We now come to the adjustment of the mounting so that its polar axis will be parallel to that of the Earth. With the two wooden mountings previously described, it will be sufficient to line up their polar axes with Polaris at any time of the night. In the case of the double fork a sight line is provided along the edge of the yoke itself, and in the all wood mounts one can line up the bent shafting. I shall, however, use the Springfield Mounting on account of its having setting circles, for the principal object in adjusting

an equatorial mounting is to be able to find the many interesting celestial objects given in many books written especially for amateurs, and to do this, setting circles are indispensable.

Let us first make sure that the axis of the mirror is at right angles to the declination axis. It is taken for granted that the declination and polar axes are square with each other. With the declination axis horizontal (see plan, at II) set up a stake at *A* (100 feet away or more) so that it appears in the center of the field of view of the telescope. Now set up stake *B* exactly in line with *A* and *C* (middle of tube), revolve the tube about its declination

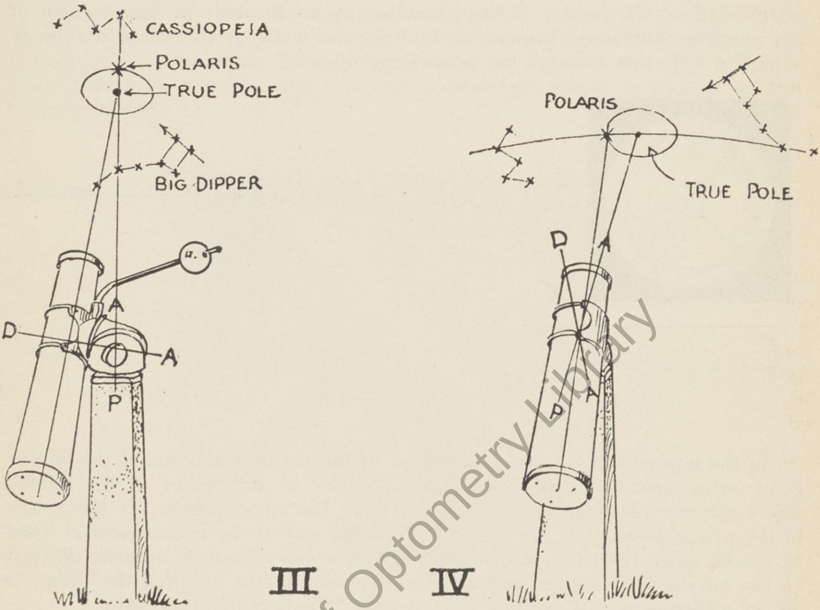


FIGURE 39

axis and see whether stake *B* is also in the center of the field. If it is not, shift the tube in its saddle by inserting shims at *E* or *F* until the image of stake *B* has moved back toward the center one-half its distance from the center. Then bring it exactly to the center by adjusting the mirror cell at the end of the tube.

Revolve the tube again, bring *A* into the center of the field (if it is not already so) by moving the entire mounting on the pier, and repeat the procedure until the two stakes appear in the field center. If they are, it is a proof that the mirror axis and declination axis are at right angles to each other.

Were Polaris (the north star) a little nearer the celestial pole (that point in the heavens where the axis of the Earth, if prolonged, would intersect with the background of the stars), we would be able to see the star in the telescope off to one side if the true pole were at the center of the field. But it is actually a little over a degree from the true pole and the field of a low power eyepiece is only about half a degree in diameter, so we must perform the adjustment in two stages shown in Figure 39, and this method applies to all telescopes, whether refractors or reflectors.

We can make the first adjustment when Polaris is above or below the pole (shown at III as just above the pole). Polaris will be above the pole when the constellation resembling a capital M or W (known as Cassiopeia) and the Big Dipper are in the positions shown in the figure. A line drawn between the star at the break in the handle of the Dipper, and the one indicated in Cassiopeia passes almost exactly through Polaris and must be about vertical when the adjustment is made.

With the tube as shown; that is, with the declination axis horizontal (the tube may be on either side of the pier), move the whole mounting on the base plate until Polaris is picked up in the eyepiece and brought to the center of the field. (Remember, the declination axis itself is not to be disturbed; the whole mounting must be moved by turning it on the bolt imbedded in the pier, and by elevating or depressing the tube.)

Six hours later or earlier (later as shown in IV of Figure 39) Polaris will have moved round in its orbit until it is at the same altitude as the true pole, that is, just west of it. Revolve the tube until the declination axis is in a vertical plane. The telescope will then be over the pier and can sweep from east to west. The tube is then depressed by adjusting the entire mounting with the base-adjusting screws until Polaris comes to the center of the field. While doing this, do not allow the mounting to turn horizontally, as this would disturb the first adjustment.

The lock nut on the central pier bolt is then screwed home.

There remains the location of the indexes, or points from which the circles are read. On a later evening, with Polaris above the pole, the declination index line or pointer should be placed or marked opposite the circle reading 89 degrees; and since Polaris is then directly north of the observer, it is in the observer's meridian, and therefore the hour angle is zero. The hour circle index should therefore be placed opposite zero on the hour circle.

CHAPTER VI.

Finding Celestial Objects. Star Time

Astronomers have covered the heavens with a net work of imaginary lines, very much as we cover the earth with circles of latitude and longitude, the only difference being that we are outside these lines on the Earth, but are inside and looking out at the celestial net work. The names they give these lines are also different. Instead of latitude they say "declination," and the term "right ascension" takes the place of Earth longitudes. Where we would fix New York on the Earth as in Lat. 42° north, Long. 5 hours west, they would locate a star as in Dec. 42° north, and R.A. (right ascension) 5 hours west; and so, as it is customary to look down on Earth objects from outside, as in I, Figure 40, we must accustom ourselves to gazing out from the Earth's center (as inside an umbrella, V) and seeing the star located as in II.

Astronomers select a certain point in the heavens from which to reckon their right ascensions, just as we agree in reckoning longitudes from a spot on the Earth's surface; viz.: Greenwich, England. Moreover, instead of going 12 hours each way from their Greenwich as we do on the Earth, they keep on clear around the heavens from zero to 24 hours. The diagram shown in II would represent a portion of the sky to an observer looking south. The northern heavens might be represented somewhat like III. To lend the sense of perspective, the circles of declination are shown as ellipses instead of circles as is actually the case.

It will be noted that as one faces the south (II) the hours of right ascension increase towards the east, but that the stars (due to the Earth's turning over) appear to move in the opposite direction—west—as shown by the arrow. On the other hand, if one looks north while the hours increase towards the east over the pole, below the pole right ascension increases toward the west and the stars in this region are apparently moving eastward (III).

The difficulty of visualizing these motions and directions lies, of course, in trying to depict on a piece of flat paper what exists on the inside of a hollow sphere. Only by continued use of the telescope and star charts will one become familiar with the heavens and sense the structure of its reference lines.

One other subject needs to be considered before trying to pick up a celestial object with the telescope; viz.: star time. If we imagine a vertical plane passing through the observer and the north pole, it will produce the line *AB* in II on the sky, and be referred to as the "meridian." As shown in the figure, if a star had the right ascension of 1½ hours it would be just crossing this meridian line and star time would be 1:30 (as indicated on the watch dial). In other words, star time *is* the right ascension of the meridian, whatever the particular R.A. happens to be at the moment. The star shown, having a R.A. of 5 hours, will not cross the meridian for 3½ hours, and (when it does) the watch will then be reading 5 o'clock. This particular star in the position indicated in II has an hour angle of 3½ hours east. Hour angles are somewhat as shown in IV, where a solid hour angle is shown cut out of a

sphere, very much like a piece of an orange. If the star to be found is west of the meridian, it has a west hour angle.

Since right ascension increases from 0 to 24 hours, like the time tables on some of the European railroads, ordinary watch dials reading from 0 to 12 hours can be used only by remembering that when star time has passed 12 hours, 13 hours will be indicated by 1 o'clock on the watch; 14 hours as 2 o'clock; and so on up to 24 hours. Dials reading from 0 to 24 may, however,

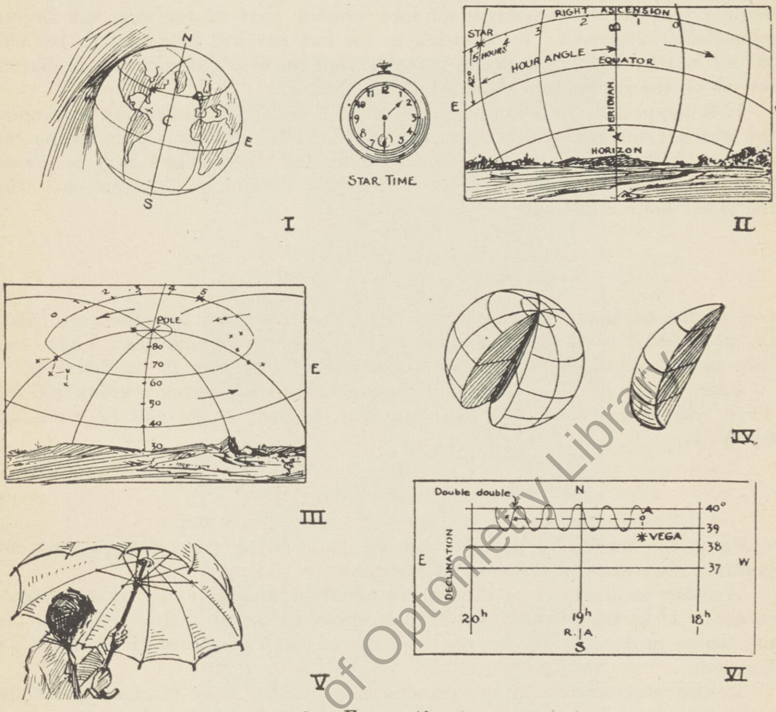


FIGURE 40

be obtained. Sometimes they are shown with the hours from 12 to 24 placed inside those reading from 0 to 12.

Several good books are available giving descriptions of interesting celestial objects along with their declinations and right ascensions. Ball's "Popular Guide to the Heavens" is one of them; Webb's "Celestial Objects for Common Telescopes" is another.

The American Ephemeris and Nautical Almanac gives the places of all the objects of the solar system and a great many of the brighter stars. The

watch is first set running on star time, by waiting until some bright, easily identified star approaches the meridian. At the moment it reaches the center of the field of view of the telescope, set the watch to the star's right ascension, remembering that if the star's R.A. exceeds 12 hours, 12 hours must be subtracted from it.

Let us take for our first object some bright star, such as Vega in Lyra, which in mid-summer will be found crossing our meridian almost overhead. Vega is so easily identified that any blunder occurring in our calculations tending to point the telescope off into another part of the sky, will become immediately apparent. Its position in the heavens will be found to be: Dec. 38° 42′ north; R.A. 18 hours 34 minutes, and the star's declination is directly set off on the declination circle of the mounting.

If it happens to be about 10 o'clock (civil time) on an evening in August, the watch (star time) will show, say, 17 hours 30 minutes. This means that all stars with this R.A. are on the meridian, and since Vega's R.A. is greater than this, also since right ascensions increase as you go into the east, then the star's hour angle will be:

18h 34m
17 30
―――――
1h 4m

east of the meridian. Therefore we move the tube over into the east (about the polar axis) until the hour circle reads 1 hour and 4 minutes. Vega ought then to be somewhere near the center of the field of view in the telescope.

Later in the evening, say about midnight, with the watch reading 19h 30m Vega will have crossed the meridian and its hour angle will be west, and equal to:

Watch	19h 30m
Star's R.A.	18 34
	0h 56m

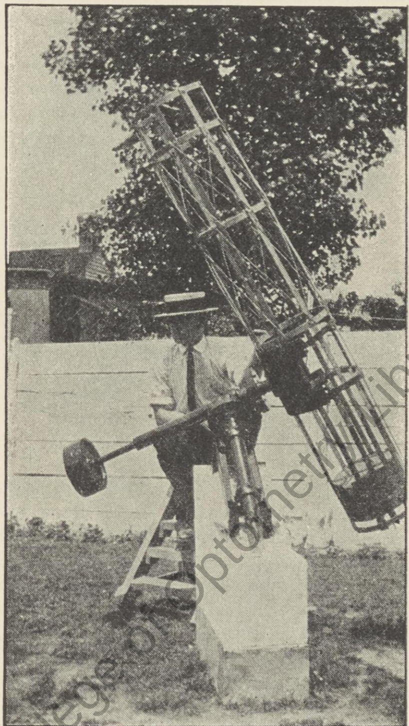
which is the setting to be made on the hour circle, the telescope tube now pointing somewhat to the west of the zenith.

Another good object to experiment on is the Moon, or any of the brighter planets. If in the daytime, we have our Sun (which is a star relatively near us) whose position in the heavens is given in the Ephemeris for every day of the year.

In this way, that is, by using the setting circles, many fascinating nebulae, star clusters, colored doubles, may be found and studied that are entirely invisible to the naked eye.

With mountings not provided with setting circles obscure objects may be located by first picking up a nearby bright star and then by two separate steps working toward the region occupied by the object in question. For example, close to Vega there is a very interesting test object, *Epsilon Lyrae,* made up of two faint stars just visible to the naked eye, each one of which is a double star. As we look up at Vega, facing south, this double double will appear in relation to Vega as in VI, though it is impossible on the small scale employed in the drawing to show separately the individuals of the pairs.

The differences in declination and R.A. between Vega and the double double are, respectively, 0° 50′ and 0h 6m, so if the tube is moved north about 1° (estimated) in declination, and then swept east in R.A., the double double will very likely come into view. There is no mistaking it when once located—two pairs of twin suns, each pair separated by only a few seconds of arc. If not found at the first try, go back to Vega and repeat the steps, perhaps moving the tube as shown, back and forth in declination as it is slowly advanced in R.A., thus sweeping over a larger area of the sky.



A HOME MADE TELESCOPE

Twelve inch mirror. Axes made from two Ford axles. The materials in the tube cost two dollars. Made by John Roney and described in Scientific American, October, 1926, page 293.

CHAPTER VII.

Telescope Housings—the Warmed Observing Room

The time honored manner of enclosing a telescope permanently mounted on its pier is by means of the hemispherical dome revolving on a circular track. A slit in the dome allows any part of the heavens to be reached with a minimum of exposure of the observer to the weather. All large telescopes are housed in this way, but these domes are expensive and difficult to make and are hardly needed for the relatively small instrument of the amateur.

It may be of interest to know what has been accomplished in the way of providing the star gazer with a closed and warmed observing room entirely independent of outside temperature. So far, in order to accomplish this end, an additional reflection has been needed in order to bring the image into the room and still preserve the principle of the equatorial mounting.

In Figure 41 are several schematic diagrams showing how the problem has been solved for refractors. In each case the mountings are meridianal sections

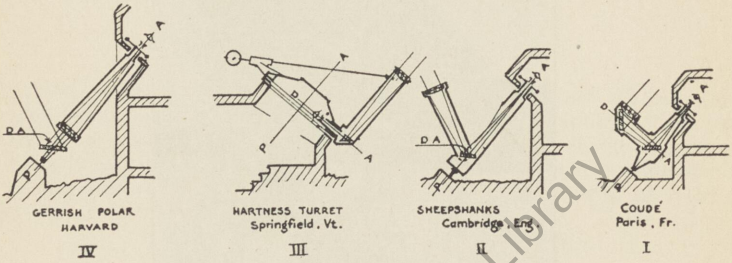


FIGURE 41

in the plane of the paper, and the polar and declination axes are lettered *PA* and *DA,* respectively. All of these types have been built and are in daily use. In I, II and IV the observer looks down the polar axis through a fixed eyepiece. In III one looks down the declination axis and the eyepiece describes a small arc of 180 degrees in covering the heavens. I and III take in the entire heavens. II and IV are cut off from part of the northern sky.

In reflectors the relations of the primary and eyepiece, with respect to the object viewed, are reversed, thus changing the problem. So far as is known, only one or two attempts to adopt the Newtonian silvered glass telescope to an enclosed observing room have been made. I used the arrangement shown at V, Figure 42, in my former home on the Maine coast for several years, but it is now dismantled. It is not recommended on account of the inconvenience of looking up the polar axis. This becomes very trying to the neck muscles after long periods of observing. This mounting was described in *Popular Astronomy,* in 1917, and the description was reprinted in the *Scientific American Supplement* for August 4, 1917.

Mounting VI is now finished and awaits a suitable site for mounting at

Springfield, Vermont. The turret carries two telescopes, a 16-inch Newtonian of 17 feet focal length, and a Cassegrainian 12-inch of 16 feet equivalent focal length, so that two observers may study the same object simultaneously.

Mounting VII might be called a polar Cassegrainian. It is just being built now at "Stellafane." And VIII, so far as I know, has never been built.

Mountings V and VII leave parts of the northern heavens obscured; VI and VIII are universal.

The upper telescope of VI demonstrates that it is possible to bring the focus of a mirror into a room without an additional reflection. I have shown

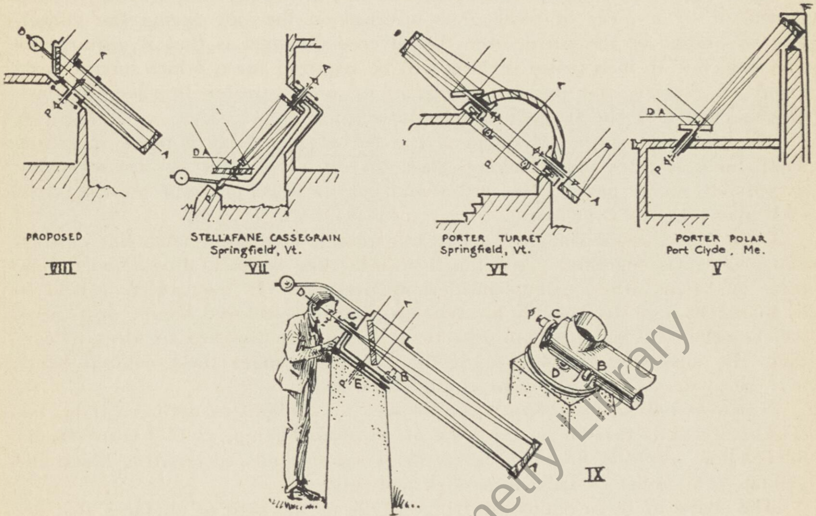


FIGURE 42

the arrangement again in IX in another position and adapted to a pier out of doors. The prism is replaced by a large flat mirror with a hole at its center. The tube carrying the two mirrors revolves in declination on the two rolls *B* and hollow bearing *C*. These supports are carried on the circular plate *D* which in turn revolves in right ascension on the stud *E*. The difficulty involved in perfecting this train of optical parts is in the perforated flat; cutting out the central hole after the mirror has been figured, results in a raised rim about the hole, due to released strains in the glass. If it is attempted at all, the central core should first be cut out and then replaced, cementing it to the glass with plaster of Paris. The whole is then fine-ground, polished and figured, and the central core is removed afterward. The perforated mirror must be very flat, otherwise any slight departures from a plane will seriously affect the image, due to the fact that it is outside of the concave mirror.

CHAPTER VIII.

The Prism or Diagonal

The essential part of the diagonal is an optically flat surface of glass placed at an angle of 45 degrees with the axis of the mirror, in order to throw the reflected cone of light from the mirror out at one side where the image formed at the focus can be viewed with an eyepiece.

This reflection may be produced in one of two ways—either by the use of a right angled prism, I, Figure 44, which will totally reflect the rays as shown, or by a piece of plate glass silvered on the side facing the mirror. The advantage of the prism over the silvered diagonal is that it requires no silvering, but an inch prism such as will be required for a 5-inch mirror costs about six dollars, and perhaps the amateur would prefer to silver his own diagonal and put the six dollars into an eyepiece.

The glass for a silvered diagonal can be obtained from a piece of broken wind shield or thick plate looking glass. We want to select as flat a portion as possible, so we get a glass cutter and cut the sheet up into several pieces each about $1\frac{1}{4}$ by 2 inches.

Clean the glass thoroughly, select two pieces, free them from lint or dust and press them together. To bring them into close contact, slide or wring one piece on to the other, using considerable pressure. If they are now held so as to reflect light from a bright area—say the sky—colored bands, or fringes, will be seen, and these will appear to be located on the two surfaces in contact. By squeezing the pieces together near the edges these colored bands may be made to move about or change their form.

Not over half a dozen bands can be seen by sunlight or artificial light, but if a little salt is thrown on the wick of an alcohol lamp, as in Figure 43, the very yellow resulting flame will show many more bands, alternating black and yellow. This must be done in a darkened room.

The shape of these bands, or fringes, tells us the kind of surfaces that are in contact—whether they are convex, concave, warped or flat. The bull's-eye in the pattern at *A,* in II, Figure 44, can be moved off the glass and given a pattern like *B* by pressing the glass together at *a.* By pressing still harder at *a,* fringes will begin crowding in from the opposite side of the glass, and the bands themselves will grow narrower *(C).* With the salt flame hundreds of these fringes may be seen until they become so fine and close together as to pass beyond the resolving power of the naked eye. This crowding in of the fringes on the opposite side from *a,* means that the surfaces are opening out on the left side, and if the pressure is moved over toward *b,* the bands will move off to the left until there are only a few left. By varying the pressure, the wedge of air existing between the two plates may be made to take any desired direction, and if the plates are convex or concave to each other, the center (or bull's-eye) of the fringe system may be made to come into view by appropriate squeezing.

What interests us is the fact that these bands may be regarded exactly like contour lines on a map. If we laid plate *A* on what was known to be

a perfectly flat glass, then anywhere along fringe 1 is half a wave length, or 1/100,000 of an inch, above or below any part of the glass along fringe 2; and 2/100,000 of an inch above or below fringe 3, depending on whether the surface of plate *A* is concave or convex. If the rings spread out on lowering the eye the plate is convex; if they close together, it is concave.

However, we have no standard flat, so we must go at it another way. A departure from flatness of one wave length of light may be tolerated, and since this means two rings, if three different pieces of glass laid one upon the other show no more than two rings, then any one of the three will answer. They must be tried No. 1 on No. 2, 2 on 3 and 3 on 1. Pick out one of a pair of plates that shows the straightest fringes.

The diagonal is so near the eyepiece that any deviation from absolute

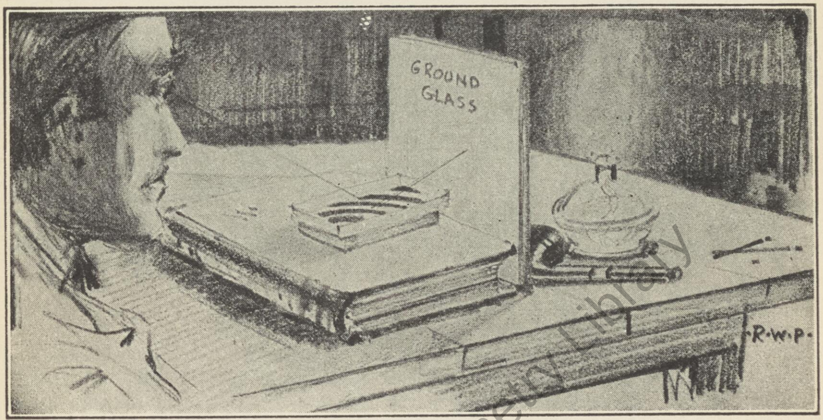


FIGURE 43

flatness amounting to less than 1/50,000 of an inch will not harm the image produced by the mirror.

The corners of the plate may finally be cut off as in II, at bottom, and the edge ground down with No. 200 carborundum on a slab of iron or glass into the ellipse shown. Silvering should be done as described in the section on silvering the mirror, and on the face of the diagonal.

While a piece of commercial plate glass sufficiently flat to serve our purpose can usually be found, one can purchase a prism blank from the Spencer Lens Company of Buffalo or the Bausch & Lomb Optical Company of Rochester, New York, for less than a dollar and grind and polish it one's self. The prism blank is first rough ground to the approximate shape, then carefully fine ground until it fits the proper templates (III). The prism is then laid, hypothenuse face down, on a slab of plate glass *D* (broken wind shield) as in IV, and four pieces of wind shield glass are laid around it as shown, cut so

as to form with the prism a roughly circular surface. The end of a tin coffee or baking powder can *(A)* is then laid over the glass, the edge of the can resting on matches *(B)*. The hole *C* has previously been cut from the end of the can. Plaster of Paris is then poured into the hole and when set, the whole affair may be slid off the slab *D* and turned over. Cut away the plaster so that the glass will be raised above its surface an eighth of an inch, and when the plaster has thoroughly dried, coat it with hot beeswax.

The exposed prism and four glass pieces are now to be fine ground on a

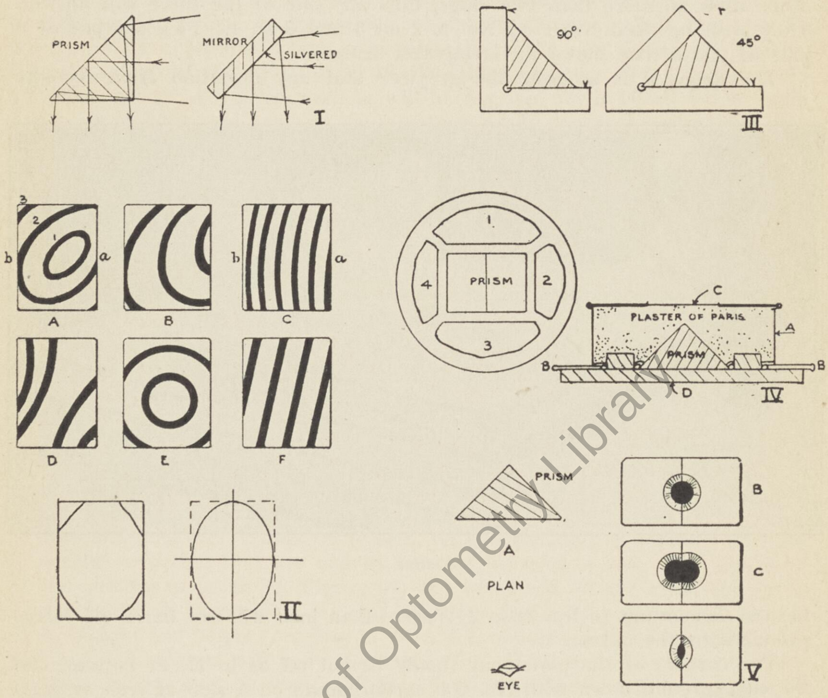


FIGURE 44

slab of plate glass and the units polished as though it were a whole disk, just as the mirror was polished.

After polishing, the prism is broken away from the plaster, turned over on one of its square faces and the operation is repeated. The other square face is likewise polished, and then the prism is finished.

The right angle of the prism need not be exactly 90 degrees for our purpose. To find out whether it is 90 degrees, the worker should hold the prism in front of one eye, about a foot away, with the hypothenuse face facing him

and its longest sides horizontal, as in V, *A*. In the prism will be seen the reflection of the pupil of the eye as in *B*, perfectly round if the angle is 90 degrees, but elongated if the angle is more than 90 degrees as in *C*, and drawn together if the angle is less. The displacement is increased as the prism is moved farther from the eye.

Now for a useful application of algebra. Pick out any three pieces of glass and label them *A, B* and *C*. Let us assume that *A* on *B* gives the fringes shown in I, Figure 45, and show three fringes convex:

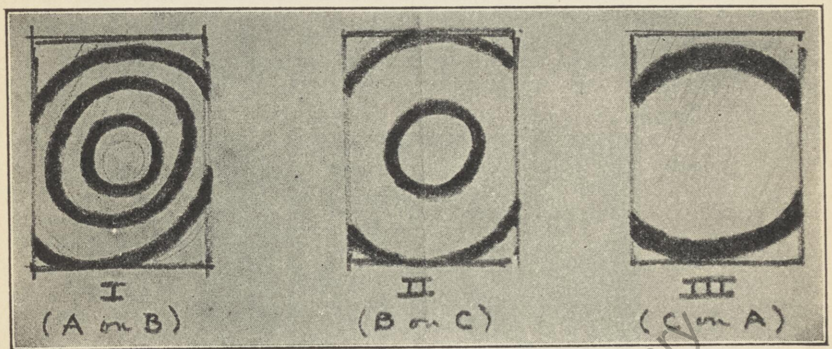


FIGURE 45

Also that *B* on *C* gives two fringes concave, and that *C* on *A* gives one fringe convex. This gives us three simultaneous equations. Then, letting the plus sign denote convexity and the minus sign concavity—

$$A + B = +3$$
$$B + C = -2$$
$$C + A = +1$$

Removing *B* from the first two equations, by subtraction,

$$\begin{array}{r} A + B = +3 \\ \underline{B + C = -2} \\ A - C = +5 \end{array}$$

Combining this with the third and solving for ***A***,

$$\begin{array}{r} A - C = +5 \\ \underline{C + A = +1} \\ 2A = +6 \\ A = +3 \end{array}$$

Substituting this value of *A* in the first equation,

$$\begin{array}{r} 3 + B = +3 \\ B = 0 \end{array}$$

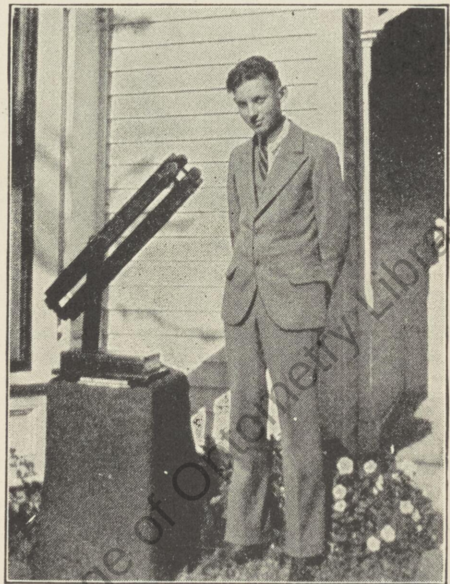
And substituting this value of B in the second equation,

$$0 + C = -2$$
$$C = -2$$

Since one fringe of yellow light is 1/100,000 of an inch, this tells us directly that piece A is three fringes $\left(\frac{3}{100,000} \text{ of an inch}\right)$ convex, B is flat, and C two fringes concave.

We can in this manner, with only an alcohol lamp, and without recourse to any expensive master flat or involved mathematics, know how flat a piece of glass is almost to a millionth of an inch.

If one of these pieces of glass were increased in size until they were a mile long, a millionth of an inch error in its surface would show up as a bulge or depression only one-fourth of an inch high—or deep.



A HOME MADE TELESCOPE

A four-inch reflector made by Frank Murray and described in Scientific American, July, 1928, page 74. Total cost under twenty-five dollars. Focal length 30 inches. Tube consists of six cypress slats screwed to a hexagonal block of wood at bottom, and bolted to an iron ring at top. Altazimuth mounting.

CHAPTER IX.

Optical Flats

Since plane mirrors are a part of reflecting telescopes where silvered diagonals are used in place of prisms, and as aids in testing both the concave at its focus as well as the two mirrors of the Cassegrainian, an account of the technique employed in making flats will be of interest to the amateur.

There are three methods of producing a true plane, each of which will be described. The first follows the time honored process of making metal surface plates of the kind so extensively used in the machine tool industry, and rests on the fact that if any three surfaces are found to be in complete contact where tried in all possible combinations, they must all of them be plane; they cannot be otherwise.

In machine shop practice the cast iron plates are rubbed on each other and the high spots scraped off until all three plates touch everywhere—say at least in half a dozen spots to every square inch. We cannot do this scraping operation on glass, and must pursue the slower and more arduous method of altering each surface as a whole on a bed or lap of pitch in very much the same way as the paraboloidal mirror is figured.

Starting, then, with three (say six inch) disks of plate glass one inch thick, each one numbered for identification, and laid out on the table, we begin by fine grinding 1 on 2, then 2 on 3, then 3 on 1, going over this sequence time and time again until it is assumed that all three are flat. Of course there is no knowing when this condition is reached until they are sufficiently polished to test by interference, but starting with commercial plate glass surfaces, two or three hours fine grinding should suffice.

The surfaces, to start with, are all flat to at least a thousandth of an inch and only No. 600 carborundum or No. 906 emery need be used. Toward the close of the cycle it is best to shorten the time of the individual wets, for if carried too long the tendency of the upper disk to go concave and the lower convex will be appreciable.

The next step is to prepare a normal pitch lap, forming it while it cools with any one of the three disks, and then giving each disk about ten minutes polishing, or sufficient to observe the interference fringes when two of the surfaces are laid in contact. (The reader should now refer to Chapter VIII, on "The Prism or Diagonal", for the manner in which these fringes are produced and interpreted). If the fine grinding has been carefully carried out, only one or two fringes will be seen and these will be in the form of perfect rings or circles like the rings around the bull's-eye of a target. (See *b* and *c* in Figure 46).

Since we must look through the disks to study these fringes, handles can not be pitched on to their backs. The grinding and polishing must be done by the hands alone.

Suppose that after solving the equations described in the last chapter, disk 1 comes out convex, it can be flattened by reducing the size of the facets of the lap uniformly from center to edge, as in *a*; or even by working over the normal lap the upper member will tend to go concave.

Should disk 2 be concave, modify the lap in an opposite manner to that shown in *a*—that is, with facets increasing in size from center to edge. Or use a normal lap on top with the disk below.

Disk 3 may be neither convex, concave nor flat, but of a real section shown in Figure 47, like the apparent section of the paraboloid at its mean center of curvature. Here we must wear away zone *x*, and I have found that the

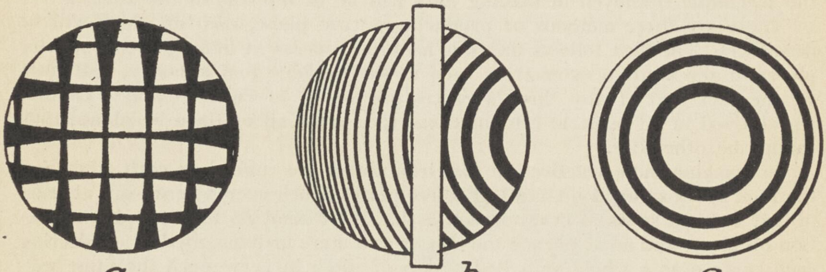


FIGURE 46

best form of lap is in the shape of a ring of pitch shown in section over the disk section in the same figure. The action of this ring, and the character of the stroke used, are identical with those involved in figuring the small convex mirror of the Cassegrain, and described in Chapter X.

During the figuring of these near flat surfaces, they should be tested frequently by interference and new equations formed. The latter method tells faithfully at any stage of the work the relationship of each surface to the theoretical plane.

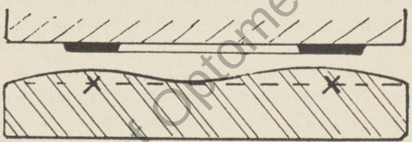


FIGURE 47

The approach to perfection can be carried as far as the worker's patience will permit, though flat to 1/100,000 of an inch is doing pretty well.

It is interesting to note that the fringes can be interpreted in two different ways: one by bringing the center of the fringe system (or bull's-eye) into the center of the disk and counting the number of rings visible; the other by laying a straight-edge across the glass and counting the number of fringes it cuts across. Thus, in Figure 46 are shown two positions of the fringe system produced by the same surfaces, the one at *c* having the bull's-eye central when

three rings can be counted, and the one at *b* showing the center well off the disk. Here, also, the straight-edge cuts through three segments of rings, giving the same result. These rings are strictly analagous to contour lines on a map.

The time required to produce a six-inch flat—say, flat to 1/100,000—by the above method, is roughly the same as making a paraboloidal mirror. Of course, only one of the three disks need be brought to a complete polish.

Care must be taken to avoid scratches when these disks are laid together for testing by interference. Rubbing one on the other to bring them together will almost surely develop a scratch. If the fringes do not appear at once on contact, separate the disks and clean each surface again. It takes only a small

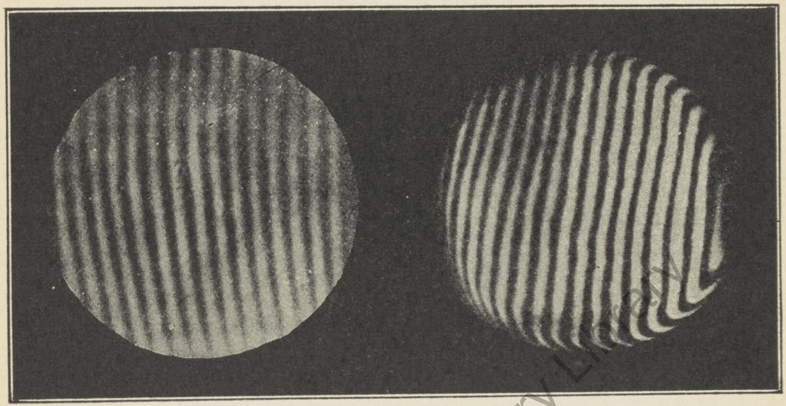


FIGURE 48—FLATS

The one on the left is ten and one-half inches in diameter, one and one-half inch thick, and is one of three made of fused quartz produced at the Thomson Laboratory of the General Electric Company, Lynn, Mass. The work of polishing and figuring was performed by John Clacey of the United States Bureau of Standards Optical Shop, in Washington, using a pitch lap three eighths inch thick. The testing was done by C. G. Peters of the same institution. The flat is accurate to one-hundredth of a wavelength, or 0.0000002 inch. Thus, if the disk were enlarged enough to extend from New York to Chicago, no point along its margin would be out of absolute flatness by more than one inch. The photograph is reproduced by courtesy of the United States Bureau of Standards and the General Electric Company. The flat shown on the right was made by Russell W. Porter and is the one referred to in the present chapter. Diameter 10 inches. The turned down edge has not been ground away or cropped out in reproducing the photograph.

particle of dust or lint between them to prevent the fringes from appearing. The palm of the hand is the best wiper to free the glass of adhering particles.

Of course, the same care must be observed in letting the disks return to a uniform temperature before testing, as is required in testing the paraboloid.

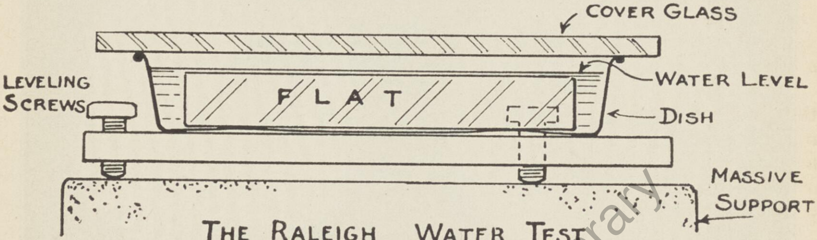
I recently figured three 10-inch disks until they all departed from flatness less than one-quarter of a wavelength of light. I photographed the fringes

from two of them in the light of a mercury vapor lamp. One is shown in Figure 48, at the right. There is a turned down edge of half a wave (1/100,000 inch). The time required was one solid month of intensive application.

The second method of making a flat and the one more likely to be tried by the amateur, since it requires but one disk of glass, is that in which the knife-edge is used in conjunction with the concave mirror of the telescope while the mirror is still spherical and before it is parabolized.

The silvered concave is set up on edge as shown in Chapter III, Figure 33, and the flat is interposed at about 45 degrees, so that the eye sees the concave mirror by reflection in the flat as though it were at *A*. If the flat is truly plane the knife-edge shadow will be of the uniformly grey appearance characteristic of a spherical surface (as described in Chapter I, Figure 11) whether the knife-edge comes in from the left or down from above.

But if the knife-edge is in one position when coming in from the left, and has to be moved in towards the mirror when cutting in from above (in order



THE RALEIGH WATER TEST FOR FLATNESS

FIGURE 49

to produce uniform illumination), then the flat is convex. If it is concave the reverse is the case, that is, the position of the knife-edge from above is farther from the mirror than where the knife came in from the left. This phenomenon is caused by the foreshortening effect due to the diagonal position of the flat.

The sensitiveness of the knife-edge test, as compared to that of interference, is roughly of the same order, at least to the extent that the amateur is likely to carry the refinements of either method.

The third method assumes that the workman can borrow an optical flat and use it for a master with which to make his own. He will fine grind his disk as flat as possible, testing it with the best straight-edge he can get hold of, bring it to a partial polish, lay it on the master and observe the fringes. If they are straight his glass is flat, no matter how close the fringes are together—his one criterion for flatness is that the fringes are straight. Of course they may be separated at will to any desired distance apart by altering the wedge of air between the disks. I usually separate the fringes about an inch apart when testing, but it is an arbitrary choice. As the air is slowly excluded and the

air wedge decreases, the fringes disappear one by one, off the thicker end of the wedge until, as the last fringe widens to the diameter of the disk, the glass is covered by one complete fringe (center at infinity), of one color, which in the case of the sodium flame (common salt), is yellow.

Theoretically we all have access to a perfectly flat surface for testing purposes simply by filling a dish with any transparent fluid and immersing our disk in it. This is known as the Raleigh Test, and is curiously intriguing from its very simplicity.

Set a basin on a firm and massive support having three adjusting screws, as in Figure 49. Place the flat in the basin and pour in water until the glass is covered by a water film about one-sixteenth inch thick. Over the basin place a sheet of glass, to exclude air currents. Now level up the glass by observing the reflections from some sharply defined point in the room, such as a lamp filament. There will be two reflections of each object from the two surfaces—air-water and water-glass. When the double reflections merge into one another the surfaces approach parallelism, and (if one's patience holds out) interference fringes will form on the glass. Of course, some source of monochromatic light must be used to illuminate the glass, such as the alcohol lamp saturated with salt.

This test sounds easy, but is far, far from it. With the slightest tremor of the water surface the fringes are gone. In using this test in the basement of my former home in Newton, Massachusetts, the arrival of a train at the station half a mile away was enough to destroy the fringes. I have never yet heard of a person making an optical flat by using a water surface as his reference plane.

It is interesting to note that a 200-inch mirror, if given this water test, even were it theoretically flat, would appear two fringes convex, from the curvature of the water surface, due to the curvature of the earth!

One might well try making his first flats by the first method described, with small disks, say of two inches diameter and a half inch thick. They are very useful in checking up the flatness of prism faces, the flat sides of lenses and in selecting pieces of plate glass for diagonals for telescopes. If one is a mechanic he can by means of them check the flatness of the anvils of his micrometer and the wear on his gauge blocks.

CHAPTER X.

How to Make a Cassegrainian

(And Why Not To)

There is something in the make-up of the Cassegrainian reflector to whet the curiosity of the amateur, intriguing him with a strong desire to construct a telescope of this type. In the first place, he argues, the addition of a small convex mirror of negligible size will quadruple the power of his instrument, or reduce the length of his tube to a quarter of what he would require in the Newtonian form of equal focal length. Then, too, he argues, you are looking straight toward the object being observed, as in the refractor, and not in at the side where the reflection of the diagonal perverts the image.

While all this is true, the amateur fails to appreciate the fact that the addition of each optical surface complicates his troubles, and that he must figure a flat mirror for testing purposes, at least as large as his paraboloid. This alone doubles or trebles the work. Furthermore, his telescope will be worthless in the daytime for looking about the country, on account of extrane-

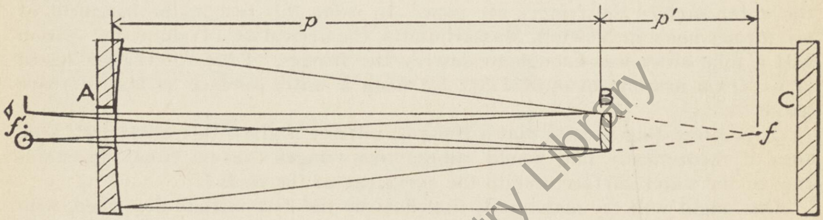


FIGURE 50

ous light fogging the field of his eyepiece. We might look at it this way: This stray light reaching the eyepiece from around the small convex mirror could be completely cut off by lengthening the tube to four times the focal length of the primary. But there is nothing to be gained here over a Newtonian of similar length and power.

However, I shall describe how the Cassegrainian combination is produced, hoping, nevertheless, that the beginner in glass working will weigh carefully the desirability of attempting one, at least until he had made several telescopes of the simpler kind.

The paraboloid *A*, Figure 50, needs no explanation to one who has made a Newtonian telescope, as it is identical with the mirror of that type, except that it has a hole at its center to permit the converging light from the small convex mirror *B* to reach the eyepiece and observer at *f'*. If the concave is made in the usual manner and the hole is cut out afterward, a miniature crater will spring up around the orifice, due to strains being relieved in the

plate glass which is not completely annealed, and it is almost impossible to remove this raised zone by local polishing without getting a turned down edge around the hole. To obviate this it is better, just before fine grinding, to cut out the hole with the "biscuit cutter" and cement the glass core back in again with plaster of Paris, with the mirror and core resting on the glass tool while the plaster is setting. Then go on fine grinding, polish, and figure; finally knocking out the core.

The secondary *B* is a convex mirror placed inside the focus of the primary, at such a position in relation to *A* and *f* as to give the desired increase in magnification. In the large mirrors on the Pacific Coast the secondary is about one-quarter of the distance *Af* inside *f*.

The formula giving the radius *r* of the convex surface is as follows: (See Figure 50)

$$r = \frac{2\,pp'}{p - p'}$$

Thus, if the concave mirror has a focal length of 48 inches and it is desired to increase this four times, the convex mirror will be placed 36 inches from the concave and 12 inches from the focus *f;* and substituting,

$$r = \frac{2 \times 36 \times 12}{36 - 12} = \frac{864}{24} = 36$$

With the radius given, the small mirror is ground and polished to an approximately spherical surface, and then figured in connection with *A* and the flat mirror *C,* by the knife-edge test, the set-up being, as shown in Figure 50, with pinhole and knife at *f'*. (The reader is referred to the chapter on making flats, for the necessary information for making mirror C.) Mirrors *A* and *C* are silvered. The three disks are lined up on edge on a bench in a darkened room, the light from the pinhole going first to *B,* then to *A,* then to *C.* From *C* it returns to the knife-edge in the reverse order. There are five reflections in all, hence the necessity for silvering *A* and *C.*

It will be noted that the returning light leaves *C* as a parallel beam, as though it came from a distant star, and the appearance of the knife-edge shadow (if all the mirrors are assumed perfect) should be that given by a spherical surface tested at its center of curvature; namely, the uniform gray of an apparent flat surface.

But the small convex surface will, at first testing, probably be about spherical, and the appearance of the shadow observed upon it will have the familiar appearance of a paraboloid at its center of curvature, with an apparent section as in Figure 47. The obvious procedure now is to wear away the apparent high zone at *xx* of the same figure, down to the apparent flat surface shown by the dotted line.

A ring lap, shown in section just over the apparent section of the mirror in Figure 47, will be found effective in reducing the zone *xx*, using straight strokes varying in length from zero to a point where the pitch ring reaches the edge of the mirror. This, in the writer's opinion, is the most difficult step in making the Cassegrainian, on account of the relatively small surface to be

worked upon locally. For a 6-inch telescope the secondary will be less than 2 inches in diameter, and to deform such a small surface in the manner shown will be attended by many trials.

Another tool useful at this time is the "rose" tool whose action is a maximum at its center, decreasing to zero at its edge. This is shown superposed over the secondary in Figure 51, *a*. The stroke may be straight, with the path of the center of the tool tangential to the circle *x;* or elliptical with the center of the tool describing the path indicated at *b, the* intensity of shading in the loops shown representing the variation in pressure applied to each elliptical stroke.

If accidental zones are produced during this local figuring, they may be reduced by a return to a normal tool.

In testing the Cassegrainian in the laboratory with artificially produced

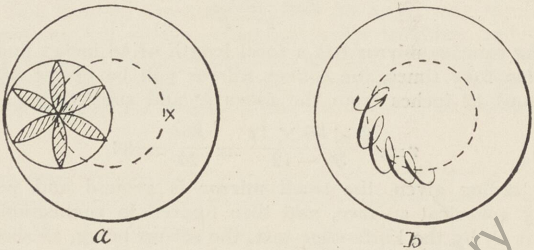


FIGURE 51

parallel light, the appearance of the pinhole image under an eyepiece will give as good (or better) definition as when the combination is used outdoors on the stars without the flat.

In lining up the three mirrors for testing, so that their axes coincide, adjustments must be provided for tilting the three surfaces.

The final surface figured on the convex mirror is said to be theoretically that of a hyperboloid.

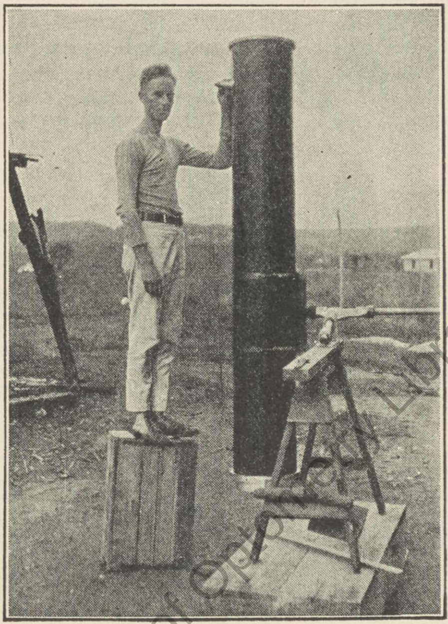
In mounting the telescope tube provision must be made for the above adjustments, as well as a movement of the convex mirror toward or away from the concave, in order to bring the resulting focus to its proper place at the eyepiece.

Referring back again to the difficulty experienced in preventing a turned down edge around the hole of the concave mirror: when the 72-inch disk for the Dominion Astrophysical Observatory at Victoria was being figured by McDowell at Pittsburgh, this trouble was overcome by packing the hole with crushed ice. This resulted in a shrinking away of the glass around the rim of the hole, allowing the pitch lap to pass over the opening without unduly wearing down its edge.

I have made three reflectors of the Cassegrainian type, so far. None of them performs as well as my Newtonians of the same equivalent focus. The

reason the large mirrors on the Pacific Coast are used as Cassegrainians is not from any preference for that type of telescope, but rather that, to secure the focal length thus obtained would in the Newtonian form be prohibited by the cost and mechanical difficulties.

I realize that these rather negative recommendations of the amateur's Cassegrainian will not deter a lot of fellows from trying it out. The simple fact that I have stressed the difficulties will be enough to attract some temperaments—like forbidden fruit. Well—good luck.



A HOME MADE TELESCOPE

Ten inch mirror. Tube shown on temporary support, before mounting, made of half-inch mahogany strips bound with cast aluminum hoops. Cell is aluminum, with four adjusting screws. The telescope was made in Guatemala, by Vard B. Wallace assisted by Dr. J. A. McKnight. Described in Scientific American, May, 1928, page 556.

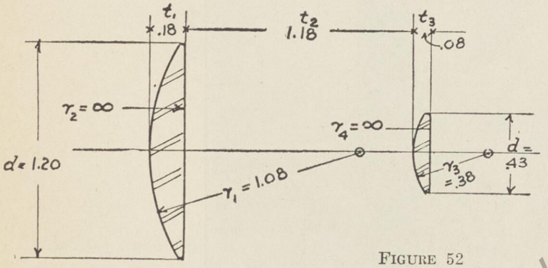
CHAPTER XI.

Making Eyepieces

The present chapter deals solely with the actual making of small lenses used in eyepieces, and the cells or containers in which they are assembled to make up the completed astronomical ocular.

The various types of eyepieces and the methods employed in testing them are covered ably by Dr. Hastings, elsewhere in this volume. I shall assume that the amateur has access to an ordinary lathe on which he may center his lenses, turn up his mount and the different laps required, and put together a simple vertical spindle similar to the one shown in the section on grinding machines, to be run by a small electric motor.

The glass blanks for eyepieces may be obtained from Donald Sharp, who carries the Chance Brothers (English) glass, or from the Bausch & Lomb Optical Co. All that is required of the amateur to secure his glass is to write to one of these firms, asking for blanks of the desired diameter and of the



RADII	THICKNESSES
$r_1 = 1.08$	$t_1 = .18$
$r_2 = \infty$	$t_2 = 1.18$
$r_3 = .38$	$t_3 = .08$
$r_4 = \infty$	

FIGURE 52

characteristics given, asking them to send glass disks having the constants nearest to these figures. Selecting, as an example, the Huyghenian ocular, the lens maker is interested only in the radii of their surfaces, the diameters and thicknesses of the components. The data are given in Figure 52. The specifications to be given the lens maker are in the table at the right. From these he constructs the drawing at the left, in order to determine the diameters of the blanks.

The field lens is first stuck to a small handle with hot sealing wax, as in *a*, Figure 53. A short section of piping or a cylinder of wood will serve as a handle. The blank is roughed to shape on any flat piece of metal or glass, to the form shown at *b*, and is then ready for grinding on the brass lap *c*.

The three laps employed have been turned up previously on the lathe and made to fit templates corresponding to the given radii. These templates are made in pairs, as at *d*. For each glass curve there should be two laps—one concave, the other convex. The reason for this is that they must be ground together in order to be sure of a truly spherical surface.

A convenient way to secure these laps to the spindle so that they may be

removed easily, will run true and not wobble, is to give the end of the spindle a taper and give the holes in the laps the same taper. The piece from which the lap is to be turned is first chucked in the lathe, as shown in *a*, Figure 54, and the hole and taper formed. The spindle itself is then chucked, the lap is driven on it and the curve is turned up with a hand tool (file) as at *b*.

The glass is now rough and fine ground on the spindle, working it across the revolving tool in short strokes, meanwhile turning it in the fingers very

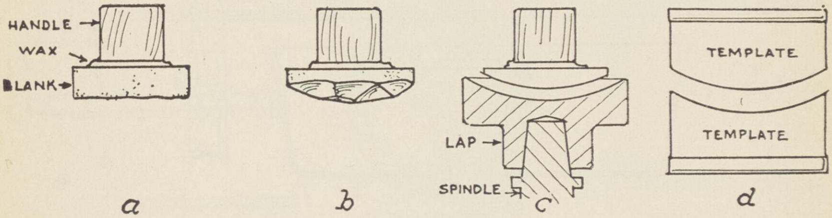


FIGURE 53

much as in grinding a paraboloid on a stationary glass tool. The speed of the lap for small lenses should be about 700 r.p.m., or roughly half that of the motor itself. A basin should be provided to catch the flying carborundum (see Figure 55, *a*). This can be made from an agate dish. A central hole permits it to be dropped down over the spindle and removed for cleaning.

If many lenses are to made singly, they are often held by a pin in a bar, shown in *b*. The glass then takes up the motion of the lap and itself spins around, the worker moving the bar back and forth while he feeds on the

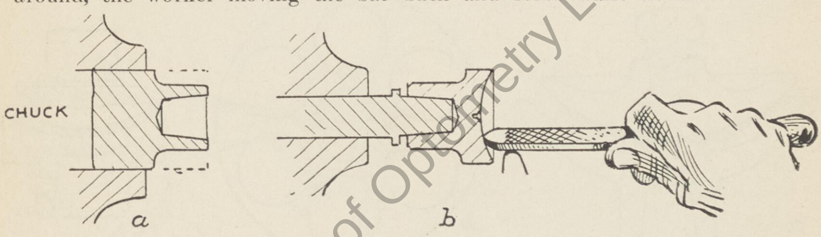


FIGURE 54

abrasive. A small metal wafer in which a shallow hole has been drilled to receive the end of the pin is pitched to the back of the glass blank. With this device the glass leaves the lap as a perfect surface of revolution, which will begin to polish evenly. But if ground by hand great care must be taken in the fine grinding to insure that the glass is in uniform contact on the lap. Where the curve of the lens is deep this spinning method cannot be used, as the point of application of the pin will be too far removed from the glass, and the lap will jerk the blank from the pin.

Where several lenses of the same kind are to be made, and the curves are not too deep, they may be combined in one unit as in Figure 56, *a* and *b*, by pitching them to the runner *A* and disposing them symmetrically in a group of seven around the central blank.

Brass laps wear out of true, and if used often should be ground together with their mates to preserve the spherical curve.

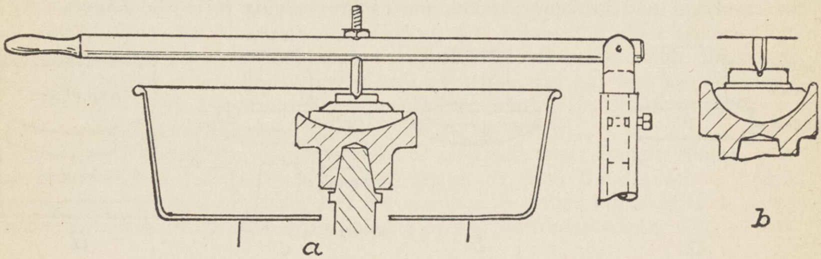


FIGURE 55

For polishing, the lap is cleaned, warmed and covered with about an eighth of an inch of hot pitch. Before it cools, the lap is placed on its spindle and formed to shape with the fine ground glass. With a sharp knife the edge is turned even and the central portion is removed, as in *c*. Heat will be generated by friction during polishing and the central hole will soon fill up. It must then be reformed.

Should polishing begin unevenly, go back to fine grinding. If it appears

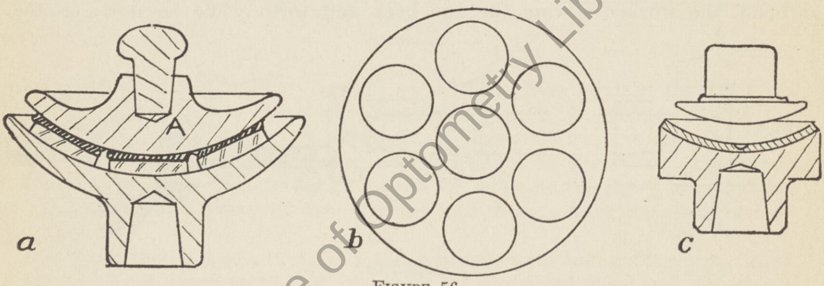


FIGURE 56

at the center, well and good—continue polishing until the polish reaches the edge of the glass, and all traces of pits have disappeared. This last inspection must be made under a magnifying glass, as the pits are too small to be seen with the unaided eye.

The glass is next warmed and the handle removed and pitched to the finished convex side, and the flat surface is ground and polished on a flat lap. The lens is then ready for centering.

The operation of centering consists of grinding down the edge of the lens, so that its optical axis is concentric with its edge. Lenses thus centered will have their axes coincident when they go into their cells assembled with the separating tube. If a lens is not properly centered we have the condition shown in Figure 57. An improperly centered lens is thicker on one side than the other. This amounts to a wedge *A* superposed on the lens, and when

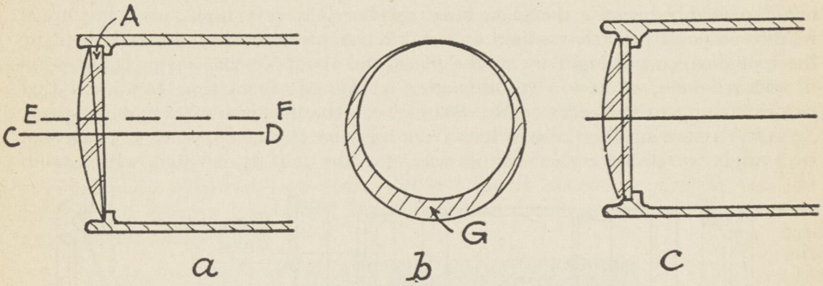


FIGURE 57

it goes into its mounting it will be lined up on axis *CD*, instead of the optical axis *EF*. The introduction of this wedge produces color, as might be expected, in the image. To correct the eccentricity the lens is rotated in the lathe in such a way as to grind away the area shown at *G*, leaving an edge concentric with the optical axis of the lens. This is accomplished in the following manner.

A piece of tubing slightly smaller than the lens is chucked in the lathe

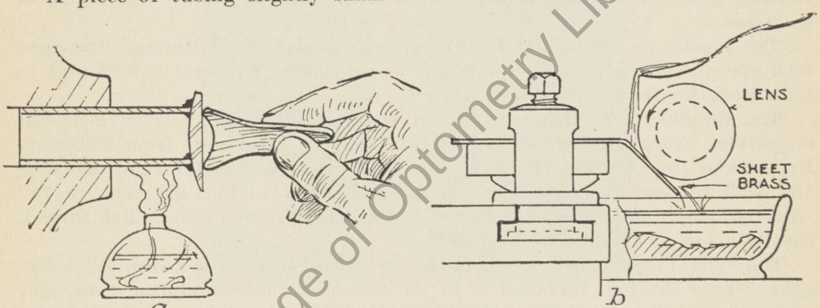


FIGURE 58

(Figure 58, *a*), and its edge is turned down so that it runs true. It is warmed by an alcohol lamp held beneath it. Sealing wax is daubed on its edge and the lens is pressed on until it bottoms against the edge of the tube. It is then rotated slowly. The glass is now seen to wobble in turning and any objects seen by reflection in the lens are not stationary, but revolve in circles. With the lamp in the left hand, warming the tube as in the drawing, a forked stick of

wood is pressed against the lens and as the wax softens, the glass will give automatically and run true. Objects reflected from it will then remain stationary.

The optical axis now coincides with that of the head stock spindle, and the edge of the lens may be turned down to the required diameter, which in our example calls for 1.20 inches.

I have never succeeded in satisfactorily turning down a lens with a diamond, probably because the glass must revolve at a very high speed, but it will readily respond to carborundum and water. A piece of sheet brass is held by the tool post and brought up to the glass, and about No. 220 carbo. is fed upon it with a spoon, as in *b*. The diameter is "miked" from time to time. Just before coming to size, shift to No. 600 carbo. Run the lathe at its highest speed.

After removing the finished lens from its tube (by heat) place it in alcohol over night to dissolve the sealing wax, for the lens is covered with carbo-

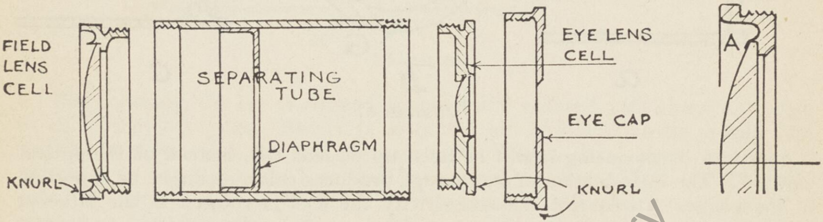


FIGURE 59

rundum and any attempt to remove the wax when it is hard will result in scratches.

The smaller or eye lens of the Huyghenian ocular passes through the identical operations required for the larger or field lens. We must now change to lathe work for the cells and separating tube.

The standard tube diameter for an astronomical eyepiece is an inch and a quarter. Stock for the separating tube may be purchased from Patterson Brothers or from Charles H. Besley & Co. It comes in just the right diameter and wall thickness, so the only operation here is to cut the tube to the required length and thread the two ends (internally) with a fine pitch thread, usually about 40 threads to the inch.

The cells (Figure 59) are turned and threaded from $1\frac{1}{4}$-inch solid bar stock. They are first threaded to fit the threads of the separating tube, and then cut off. One of these blanks is then screwed into the separating tube which is chucked so that it runs true, and the remainder of the cell is turned, leaving a recess a thousandth of an inch or so larger than the lens it is to accommodate.

The lens may be fastened in its cell with shellac or black sealing wax, or it may be crimped in by turning up a thin edge *A* and crimping it over against the glass with a small roller, running the lathe at its fastest speed.

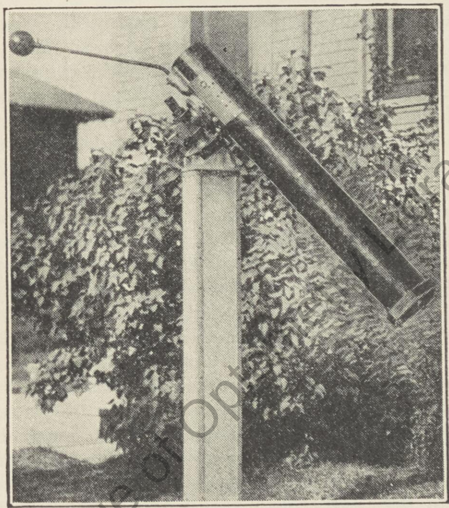
If an eye cap is desired the eye end of the separating tube is threaded

externally and the cap is made as shown in the figure. Finally, the diaphragm is turned up and moved in the tube to such a position, by trial, that the edge of its aperture appears sharp when looking through the eyepiece. The diaphragm and inside of the tube are then painted a flat black.

The cells and cap are given a dark oxidized surface by immersing in nitrate of copper (dissolve some pieces of copper in nitric acid) and then heating in the oxidizing flame of a bunsen burner.

If a higher powered eyepiece is desired than the one here specified, all the quantities in the table are divided by such a factor as will give the desired increase in magnification. For example, an ocular of half the equivalent focal length (or double the power) will be arrived at by dividing all the data by 2. This does not hold true when it comes to the mount, as the lenses diminish in size, while the outside diameter remains constant, viz., an inch and a quarter.

There is no short cut to a really good, efficient ocular. I know of no way of producing an eyepiece free from faults without access to a lathe, and in writing this chapter I have had in mind that group of young men who have an aptitude for this kind of work.



A HOME MADE TELESCOPE

Six inch mirror. Springfield mounting made up of two Ford front wheel assembles secured at the auto wrecker's. Declination axis is a $1\frac{1}{2}$ by 3-inch nipple, threaded from end to end, and has a Timken roller bearing from an old motor car. Pedestal is made of $\frac{3}{4}$-inch angle iron and light galvanized sheet metal fastened together with stove bolts, and is very rigid. Made by H. O. Bergstrom and described in Scientific American, December, 1928, page 555.

Part II.

THE AMATEUR'S TELESCOPE

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CHAPTER I.

Introductory

Nearly 150 years have passed since William Herschel, then the unknown organist of Bath, began those experiments in telescope construction which in a few years made him the greatest astronomer and greatest master of the telescope that the world has yet seen. The Newtonian reflector was his chosen form of instrument almost of necessity. The achromatic lens was as yet in its infancy, and the Gregorian construction was too complicated for an experimenting amateur, and was, besides, only suitable for small sizes, and consequently limited in its possibilities.

A distinguished band of workers have, during the past century and a quarter, followed Herschel's lead, and nearly all have imitated his preference for the Newtonian, although the achromatic object-glass has become such a formidable rival to the concave mirror. The reason for the popularity of the Newtonian is still the same as in Herschel's day. It is the amateur's telescope, because, now, as then, it is the easiest to make and the easiest to mount, and far the cheapest either to make or to buy of any class of telescope. And, though cheap, it is not "cheap and nasty."

A good mirror is to the astronomer a thing of beauty and a joy for ever, capable of unfolding all the myriad glories of the heavens and of holding its own with the most costly products of the optician's art in definition and power. The names of those who have worked on it and helped to perfect it include many of the very brightest lights of the world of science in the nineteenth century. Lord Rosse, Lassell, With, Calver, Draper, Common, Foucault, Liebig, all gave of their best brains to the problems—most fascinating and alluring problems they are—set for solution by that beautiful sphinx, the paraboloidal mirror. That simple-looking disk of glass, with its almost imperceptible curve, shows little indication of the magical and mysterious powers which lie latent in it, powers to open to the astonished gaze a universe of glory and wonder; or of the amount of thought and anxious endeavor which have gone to the perfecting of its subtle curve and the depositing of its shining skin of silver.

Briefly, the advances since Herschel's time have been:—(1) The invention of the method of depositing a film of silver on glass by Liebig, improved later by Brashear and others, which made glass possible as a material for optical specula; and (2) Foucault's lamp and knife-edge, which made it possible for the workman to see exactly what he was doing while figuring the reflecting surface.

It was unfortunate that Foucault's test was not known to With. Had it

been, it would have immensely increased that great master's output, and also improved the quality of his work. As it was, Calver, though little, if at all, With's superior in skill, reaped the harvest of accuracy which With just failed to gather in. Many of With's specula have been retouched, to their great benefit, both by him and by the present writer, though one always handles a With mirror with reverence and wonders at the skill which could come so near perfection working in the dark.

Perfection—that is what the concave speculum has attained of late years. It is possible for a worker of sufficient skill and experience now to set about making a mirror, secure in the knowledge that he can produce a surface in which the most extraordinarily delicate test the human brain has ever devised can detect no flaw. Nay, more, he can produce a mirror whose accuracy is really *beyond* the requirements of telescopic vision. A mirror which has faults quite visible to the expert using Foucault's test will often perform in the telescope just as well as one which has none, because the faults of the faulty one are too small to affect the visual image. The test is, in fact, *unnecessarily* delicate. But then nothing is ever "good enough" so long as it can be improved, and no good speculum maker will let a mirror out of his hands which has a defect which he can see and can remove, however small that defect.

The earnest and industrious speculum worker never really knows to what his efforts may lead him. In most trades the amateur must be content to follow humbly, and at a distance, the steps of the trained professional man. In telescope-making, and especially in the making of the essential parts of the reflector, it is the other way about. The amateur has shown the way to the professional, and forced the pace for him, ever since Herschel's time. Herschel himself was an amateur, so was Lord Rosse, so was With, so were Draper, Common, Calver, Wassell, and Alvan Clark. That many of these *became* professionals only emphasizes the fact that they began work as amateurs and ended by beating the professionals at their own trade. That they did so is largely due to their recognition of the principle expressed in the phrase I have just now used. "Nothing is 'good enough' so long as it can be improved."

The chapters which follow are dedicated to the amateur telescope makers of the world in the hope that some at least of them may be thereby helped on the road which led Herschel, With, Calver, and Clark from humble amateurism to the headship of the world's professional makers. The writer's first telescope was constructed when he was aged ten years, and consisted of a spectacle lens, a sixpenny microscope, and a pasteboard tube, with which humble instrument, innocent of achromatism, he first viewed Jupiter's satellites, the phases of Venus, and the lunar mountains. This was the beginning of the ladder which has already (1920) reached seventy mirrors of apertures from 6 to 12 inches, and object-glasses of 4, 4½, 5, and 5¼-inch aperture.

Literature

The beginner who seeks for literature to direct his efforts will meet with the difficulty that most of the works on the subject of speculum making are

out of print, or buried in back numbers of magazines, especially those of the *English Mechanic.* Draper's papers are only to be got at in the records of the Smithsonian Institute. The very excellent articles of Francis may possibly be obtainable in a public library in Vol. VII of *Amateur Work.* Wassell wrote in the *English Mechanic,* 1881-3. Browning's "Plea for Reflectors" and Horne and Thornthwaite's "Hints on Reflectors" are both out of print, as is also a useful little book by W. Banks, F. R. A. S. The only thing of the kind still in print is a helpful chapter on the subject in Hasluck's "Glass Working by Heat and Abrasion," published at 1s. 6d. by Crosby Lockwood & Co.

Even if all these were obtainable they have one defect in common. They are more or less out of date. The most recent of them represents the state of progress in the art of mirror making existing in 1890-95 or thereabouts. And if nothing else had happened since then, the invention of carborundum in 1898 was sufficient to revolutionize the whole process of grinding, and to place emery out of court as an abrasive. This material, a carbide of silicon, and manufactured much in the same manner as carbide of calcium, was first made at the Niagara Falls Electric Works, and began to come into use for glass working about 1900. In that year the writer obtained a sample in Dublin, and since then has used no other grinding material, except for the very last stage of fine grinding. Carborundum cuts about six times as fast as emery, and with No. 80 a 6-inch mirror can easily be rough-ground to curve in less than half an hour, and the whole process of grinding can be done in two and a half to three hours.

CHAPTER II.

Tools and Materials

For the amateur, speculum-making has one great advantage; it does not require an extensive or expensive outfit of tools. Indeed the essential ones need not cost more than a very few shillings. Opticians, it is true, use cast-iron or brass tools, carefully made to gauge and ground true, for forming the curves both of lenses and specula. And where a large number of curved surfaces have to be produced, all of the same radius, these are indispensable. But for the purposes of the amateur mirror or object-glass maker glass tools are preferable, and both their cost and the trouble of making them are negligible. Here, then, is a list of the things necessary to be provided before we begin. It is neither long nor costly:—

1. A pair of equal glass disks.—One for the mirror, the other for the tool. The mirror-disk should have a thickness not less than one-eighth of its diameter—perhaps one-sixth is better still. The tool may be of lighter stuff.

2. A barrel—or, better still, two barrels.

3. A pound or two of pitch.—There are three kinds usually on the market—English, Russian or Archangel, and Swedish or Stockholm. Any of these will do, but Swedish is commonly preferred. As now sold, no cleaning or straining is needed. Purchasable of chemists or oil and color shops.

4. Carborundum, No. 80, 220, FFF.—15M., 30M., and 100M. powders are suitable and sufficient. Sold in 1-lb. and 2-lb tins. Buy from the makers, on no account from the "local shop," or grades may be found disastrously mixed.

5. Jeweler's rouge.—One pound will polish quite a number of mirrors.

The above are indispensable. To these may be added a list of articles not indispensable, but very desirable:—

a. A lathe.—The possessor of a lathe can turn up the blocks and handles which he requires for mounting and holding disks during working, and can do a lot of neat jobs when he comes to mount his mirror and flat. To *make* a flat a lathe is indispensable.

It is very desirable that the grinding and polishing should be done in different rooms. If the worker is lucky enough, or rich enough, to possess the house-room for this, the polishing-room should be provided with its own barrel, and nothing contaminated with carborundum should on any account be allowed to enter it.

b. An oil-stove or gas-ring is almost indispensable for melting pitch, warming glass disks before cementing, etc. (Pitch will not stick to cold glass.) —If the worker resides out of reach of gas and uses an oil-stove, it should be of the central-draught variety, with a circular burner, and its upper works should be stout enough to support a fairly heavy weight.

c. An assortment of enameled iron dishes and basins will be found useful for quite a number of purposes, such as holding water and rouge, and covering tools and mirrors to keep off dust during the intervals of working. Porcelain or earthenware ones are objectionable, owing to the danger of damaging a mirror by an accidental blow against them.

If the worker possesses a lathe, his first job will be to turn up handles and supports for tools and mirrors out of hard wood (oak, box, or mahogany for choice). The usual way of mounting the glass tool is to cement it to a disk of wood an inch or two larger in diameter than the glass. The disk has a wide bevel, and is gripped by three large countersunk screws, the heads of which hold the bevel, as shown in Figure 1, left.

A preferable plan, however, is to have a thick wooden disk, considerably smaller than the glass, screwed securely and concentrically to a stout sheet-iron disk somewhat larger than the glass. The edge of this is gripped by three screws, with a small washer on the head of each. The glass tool cemented to the wood forms a sort of mushroom top. The advantage of this is that it enables us to keep the whole arrangement clean.

Get a sheet of thin zinc, and cut a circular hole in it the size of the wooden disk. Then cut it across, dividing the hole in two. This is placed under the tool, while grinding, with the two semicircular openings closely embracing the wood disk and catches the mud and water which drips from the tool. It is removed and washed as often as may be required, and saves a lot of mess and much risk of scratches in the fine-grinding. (Figure 1, right.)

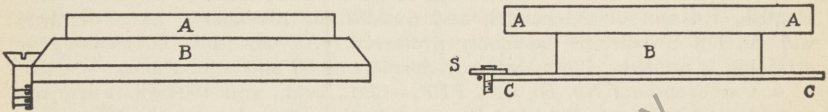

FIGURE 1

TWO WAYS OF ATTACHING THE TOOL TO THE WORK-STAND

Left: A is the tool; B is the beveled disk of wood. Three wood screws hold it in place. Right: AA is the tool; B is a thick, wooden disk; C is a disk of sheet iron; S is one of three screws, with washers. Drip from the edge of A may be caught by sheets of thin tin, cut to fit close to B.

It is well to have a piece of soft deal plank, nicely planed up, and cut to fit on the top of the barrel, to which it is secured with screws. To this the various disks carrying tools are screwed, and when frequent screwing and unscrewing has damaged the wood beyond repair it can be easily replaced. Another disk, smaller than the glasses, must also be turned up. It should be about 3 inches diameter, and is for the handle to hold the mirror. A socket is turned in the center of it, and a cylindrical piece fitted and glued or pinned in place. Now attach the handle to the mirror and cement the tool to its wooden disk, and screw the latter to the barrel top, and we are ready to begin.

Rough Grinding

The next stage is roughing out the curve. The tool is warmed, slightly smeared with spirits of turpentine, melted pitch is poured on the wooden beveled disk, and the smeared side of the glass pressed down on it, squeezing out the excess all round. When cold, the disk is attached to the barrel top. We next warm the back of the mirror, smear a little turps in the center, pour sufficient melted pitch on, and press the handle firmly on. When cemented on it looks like Figure 2, center.

Ordinarily 8 oz. cocoa tins are convenient for melting pitch in. Of this more later on, when we come to polishing. We place a basin of water and a handful of absorbent cotton handy on the work bench and a tin of No. 80 carborundum, strew a little carbo. on the top of the tool, dip the face of the mirror in the water and place it on the tool.

We must now make acquaintance with the mirror maker's "three motions." In order that the desired curve may be produced, the upper disk must (1) travel to and fro across the lower, (2) rotate about its own center, and (3) the worker must walk slowly round the barrel. It is obvious that these three motions could easily be produced by machinery, and for grinding such a machine would work admirably. But it would fail in polishing and figuring. The labor of grinding a mirror of moderate size is not great, and

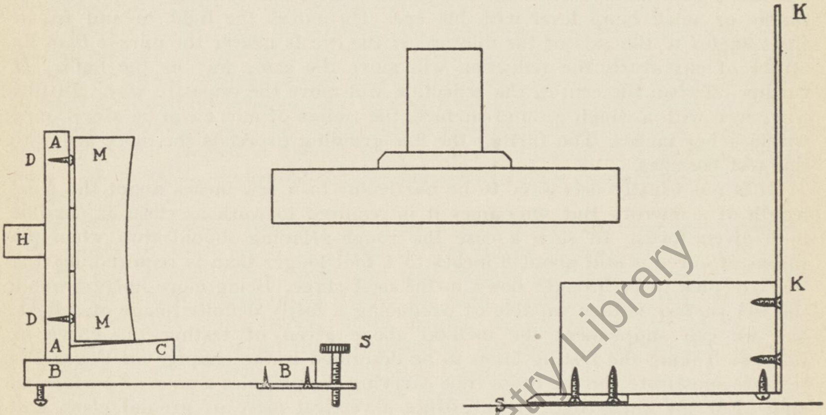

FIGURE 2

THREE NECESSARY ACCESSORIES

Left: The adjustable easel for carrying mirror when testing. Center: the glass disk with wooden handle attached, ready for work. Right: the knife-edge on its block—ED.

hand work is all that we shall need. Motion (1) is known as the "stroke," and by lengthening or shortening it we can produce most useful modifications of the curve. In roughing out, a long stroke is useful—*i. e.,* one as long as possible when the center of the mirror reaches the edge of the tool at the end of each traverse. It produces an irregular curve, of greater depth in the center; but at present this does not matter, as we are more concerned about excavating a hollow as quickly as possible than about its shape. The shape will quickly come right when we begin fine-grinding and shorten the stroke. An ellipitical stroke, or "side" stroke, is useful for some purposes, but it slows the cutting.

After working for a few minutes the charge of carbo. begins to get dry; so we lift the mirror and add a few drops of water, and so go on till the

feel of the grinding tells that the abrasive is ceasing to cut. We then lift off the mirror and renew the charge. The older authorities recommended washing the tool and mirror to remove the mud which has accumulated. But this is not necessary at the present stage, and wastes time and labor.

When it is deemed advisable to try how deep the curve is, then we must wash the mirror free from all traces of abrasive, using for this purpose the cotton before mentioned. Absorbent cotton is used instead of the sponge once recommended, because when each stage of grinding is completed the cotton can be thrown away and a fresh, clean bunch taken for the next stage, thus avoiding all possibility of carrying over grit from one operation to another.

To test the curve, the mirror is stood on its edge on a table or shelf, with its surface well swilled with water to make it reflective. The worker stands before it, with his eye on a level with its center, and holding in one hand a candle or small lamp level with his eye. He moves the light to and fro at right angles to the axis of the mirror. If the eye is nearer the mirror than its center of curvature, the reflection will move the same way as the light. If further off than the center, the reflection will move the opposite way. In this way, even with a rough ground surface, the radius of curve can be ascertained within a few inches. The further the fine-grinding proceeds the more accurate this test becomes.

It is not usually necessary to be particular to a few inches about the focal length of a mirror. But sometimes it is required to work as close as possible to a given focus. In such a case the rough-grinding should stop when the radius of curve is still about 8 inches to 1 foot longer than is required, leaving this overplus to be brought down in the next stage. Being more finely ground, the wet surface is then capable of producing a fairly definite image of a light, and we can supplement the method above given of testing the curve as follows: Taking the testing lamp to be described in the chapter on Foucault's test, we substitute for the brass tube carrying the pinholes a tube of perforated zinc. For the knife-edge we substitute a vertical piece of ground glass, and mount this and the lamp abreast on one base. By placing these in the center of curvature of the mirror, we get an image of the perforated zinc thrown on the ground glass. When it is focused as sharply as possible, the distance from mirror to ground glass is the radius of the mirror's curve. A long lath marked in feet and inches is useful for measuring.

It is well to remember that the radius of curve usually shortens about ½ inch in the process of polishing, and this should be allowed for if an exact focus is to be worked to. With care, it is possible to get within ¼ inch of a given focus.

Having roughed out the curve to within a little of the required depth, the next step is to cleanse away most thoroughly all traces of the coarse abrasive. The mirror is well sluiced with water, the tool and its block are detached from the barrel and sluiced under the tap, and crevices scrubbed out with a brush (an old tooth brush is excellent), and the top of the barrel is also well washed with plenty of water.

Now we replace the tool in position, throw out the water in the basin and the old cotton, get a fresh handful and refill the basin with clean water. We

now proceed, using 220 carbo. If the curve is very near the required depth, we shorten the stroke to one-third diameter; but if we are still several inches off the required focus it must be kept long for the present.

If the curve requires no further deepening, six "wets" of 220 carbo. will suffice for this stage. (Each time a charge of carbo. is ground down and a fresh lot applied with water is called a "wet.") Five minutes is an average time for a wet; so each grade of fine-grinding will last roughly half an hour.

We may here add that if a very long stroke has been used in roughing the first effect of changing to short stroke may be to lengthen the radius of curve a couple of inches. It will, however, shorten again, though more slowly, and the effect of the short stroke will be to bring the curve of the mirror approximately to a part of a sphere which is what we want at present. We must persevere with 220 carbo. till the desired radius is quite reached, for the effect of subsequent grades in deepening the curve will be almost nil.

When at length ready to proceed, the washing-up process is carefully repeated, and we change to F F F. Six wets each of this, of 15M., 30M., and 100M., are given, washing up with care after each grade of powder. There is no need to elutriate carborundum, as was formerly done with emery, to obtain the finest grades of all. No finer can be produced than the 100M. * supplied by the makers. Indeed, it may be doubted whether this gives any finer surface than 30M. or 60M. Polishing may be commenced on a surface fined with any of these three.

But we may with advantage use a sixty-minute settling from finest washed flour emery to finish with. A pound of this emery is placed in a large glass jar, the jar is filled with water and well stirred, and then let stand for an hour, after which the liquid is drawn off with a siphon of rubber tube into another jar, care being taken not to disturb the emery at the bottom. The siphoned liquid is let stand till it deposits all the solid matter suspended in it, and this sediment is used to give the final fining to our mirror.

Great care is necessary in this final stage, and also with 60M. carbo. The quantity of abrasive between the close-fitting glass surfaces is so small that they sometimes seize each other and cling so fast together that it is difficult to separate them without a serious scratch. If the disks begin to cling, they should be slid apart at once, lest worse happen.

When the mirror is properly fine-ground it will be possible to read large print through it at some inches distance, or to obtain sharp vision of the sashes of a window at several feet. But the beginner should beware of accepting this as an infallible test of fitness for polishing, as it may consist with the presence of large pits and scratches surviving from the coarser abrasive. The best safeguard against these is to be thorough in the earlier stages of the fining.

The six wets of each grade above described will be found sufficient, if care is taken to grind each down completely. Pressure on the glass is a help to the thoroughness of the grinding, and can have no ill-effect provided the thickness of the mirror is not less than the 1/6 diameter before prescribed.

* This size is no longer manufactured in the United States.—Ed.

Some workers wash the surface of both mirror and tool with the cotton after each wet, but this is not necessary, though perhaps advisable in the 30M. and 60M. stages.

The writer has always made a practice of mixing the finer carbo. grades (15M. to 60M.) with alcohol, and keeping them in corked bottles. The bottle is shaken and a few drops poured out on the tool for each wet, a few drops of water being added. These powders are so clinging that it is difficult to distribute them over the tool dry, and they do not readily mix with water. Moreover, a certain gradation of fineness can be obtained by shaking the bottle vigorously for the first wet, less vigorously for the second, and so on, and very slightly for the last.

Another way of obtaining a final fine-grinding is by making a pitch-tool out of hard pitch. After 60M. is finished with, we carefully wash all up, and replace the tool on the barrel. Dry the surface with a cloth, and smear a little spirit of turpentine over it with the finger tips. Now melt some hard pitch in a tin over the oil-stove. It must be quite thoroughly melted. When completely liquefied, smear the face of the mirror thoroughly with a lather of soap and water, pour the melted pitch all over the tool, take mirror at once and press it down on the soft pitch, moving and twisting it about till the pitch is judged hard enough to retain its shape of itself. Now slide the mirror off, and you have a pitch surface of the same curve as the mirror itself. Let this cool completely, and then apply a thin layer of the 60M. carbo., mixed with alcohol, all over it. Work the mirror on this in short strokes for from ten to twenty minutes, and you get a semi-polished surface, which, if thoroughly done will polish on the rouge tool in about three hours' work instead of the usual six. This method of doing the last stage of fining has the merit of being perfectly safe, both from seizing and scratches.

It is in the last stages of fine grinding that scratches usually originate. A scratch during polishing is rare, and can only result from carelessness, such as approaching the polishing tool with garments or person contaminated with grit, leaving the tool exposed to dust, "spring cleaning" the room when polishing is in progress, etc. (N.B.—The polishing room should *never* be swept, and no feminine hand should ever be allowed, on any pretext whatever, to "tidy" it. Total destruction of a polished surface may be the result of neglect of this rule. "Let sleeping dust lie" should ever be the mirror maker's maxim. It will do less harm on the floor than on his tools or on optical surfaces. A lock on the door and the key in his pocket is the best safeguard.) But all endeavors should be directed to securing immunity from scratches in the fine grinding. Extra care in the washing of tool and barrel and mirror, the provision of a separate basin for the final operations, and covering the work bench with sheets of clean paper will usually secure a clean surface on which to begin the polishing. Very slight scratches need not be regarded, as they will polish out. But even serious ones will often be invisible on the fine ground surface, to start into conspicuous and ugly visibility when polishing begins.

Many workers recommend the use of a pocket lens to examine the surface after each stage of the grinding, in order to ascertain whether all marks left by previous grades have been ground out. The experience of the writer is not

favorable to this as a test. Even the microscope is not always able to tell whether a surface is well or ill prepared before polishing has been begun. The large deep pits and scratches are so disguised by the presence of the mass of small ones that the most experienced eye may fail to detect their presence. It is only after about half an hour's polishing that they start into disastrous prominence. The only real safeguard is to be very thorough with the last, or last two, stages of the fine grinding. Carborundum cuts so fast that 30M. or 60M. will quickly remove even quite deep pits and scratches, and if any doubt remains as to the existence of these, a double dose of 60M. will usually make sure of them. A plan which the writer has sometimes practised is to make a scratch with a diamond somewhere near the middle of the tool, deep enough to be quite certainly deeper than any possible abrasive pit. The edge of the mirror and middle of the tool are the parts which grind most slowly. Therefore, when this scratch grinds out, it may be confidently assumed that all lesser pits are gone.

For the reason just mentioned, that the edge of the mirror gets the least grinding, it is a very good plan to do the last stages of the fine grinding with the mirror face up, reversing the relative positions of mirror and tool. The "mushroom" form of support already described (Figure 1, right) will facilitate this change. In this way that part of the mirror which polishes most slowly (viz., the edge) will get the most fine grinding, and the benefit will quickly become manifest when polishing begins.

CHAPTER III.

Testing; Foucault's Shadow Test

As soon as we begin to polish we immediately require some means of ascertaining what is happening on the concave surface of the mirror, though this knowledge is not of the greatest importance until later on, when we begin the most difficult process of all, viz., the figuring. We might, indeed, go ahead with the polishing, confident that no irremediable error would develop in the curve, so long as the tool was made and used as we shall describe by and by.

Once upon a time it was believed that if a figure of a mirror once became hyperbolic it could not be remedied, and all sorts of devices to avoid the "fatal hyperbola" were resorted to. As a matter of fact, a hyperbolic mirror, though less easy to remedy than some other faulty curves, presents no difficulty to a moderately expert hand, and we could, if we desired, polish away merrily till all marks of abrasion had disappeared, without any testing at all, careless which of the list of possible regular curves turned up at the end of the process.

There are only two limits to this possibility: (a) the limit of human endurance, which prescribes that half an hour's polishing at one spell is enough for the worker's patience; and (b) the limit of endurance of the pitch tool, which begins to soften, from the heat produced in polishing, if one goes on much longer without letting the tool cool down. To this we may add human curiosity, which naturally desires to see how the figure is shaping.

Up to the time of With, speculum makers had to work in the dark, except for tests upon stars, for which one had to wait till the sky chose to clear, and also to dismount the mirror from its handle and mount it in a telescope tube. Naturally, mirror making under these circumstances was a slow and uncertain process. It is owing to the genius of the great Frenchman Foucault that we now have a simple and easy method by which the figure of a mirror is made actually visible to the eye, and so delicately visible that the expansion due to the heat communicated to the glass by the touch of a finger can be clearly seen.

Foucault's method consists essentially in the provision of an artificial star, in the form of an illuminated pinhole. This, of course, cannot be placed at a great distance, so that the light from it will be sensibly parallel, like that of the real stars. It is therefore placed at the center of curvature, and although the resulting appearances differ from those seen when parallel light is converged by a mirror to its principal focus, the two sets of phenomena can be connected by a simple formula.

If the pinhole be placed at the center of curvature of a spherical mirror, it follows from optical laws that all light from the pinhole falling on the mirror will be reflected back exactly to the pinhole again, and will form an image of the pinhole, the same size as the pinhole, on the pinhole. In this position it could not be examined. We therefore slide the lamp a few inches to the left, causing the image to move the same distance to the right, where it can either be examined by an eyepiece or received direct into the eye. Both methods are useful. If the image be allowed to enter the eye, the mirror is seen full of light, like a full moon. Now comes in the second part of Foucault's ingenious plan.

A vertical knife-edge is mounted so that it can be made to slide laterally across the path of the pencil of light, close to the point where it focuses just before entering the eye. When this is done the eye sees the shadow of the knife-edge cross the mirror. Hence the name "shadow test." But the manner of its crossing differs according to the position of the knife-edge with respect to the focus. If it cuts the beam within (nearer the mirror than) the focus a vertical shadow crosses the bright face of the mirror the same way that the knife-edge moved. If it is *outside* the focus, the shadow crosses the opposite way. If it be exactly *at* the focus, the surface of the mirror darkens all over evenly, and looks flat, no moving shadow being seen either way. These are the appearances characteristic of a sphere.

But if the mirror is not spherical, but has some parts of a greater and some of a lesser radius, however small the difference, what will happen? Obviously we shall see the shadow broken up into parts crossing the mirror opposite ways, if the knife-edge is so placed as to be within the focus of some parts and outside that of others—and that however minute the difference may be.

In practice the mirror is mounted on a kind of easel having one screw-foot in front, as a fine-adjustment for raising and lowering (Fig. 2, left). The lamp should be as small as possible, and it is convenient if it can be made to sit in one of the rings of a retort stand, so that it can easily be clamped at any height. A brass tube, with two or three pinholes of different sizes, drops over the chimney. The knife-edge is a vertical strip of steel with a sharp edge, mounted in a wooden block weighted for steadiness and having its forward edge provided with a smooth metal straight-edge (Fig. 2, right). The object of this will be seen later on.

The whole apparatus, with its table, should rest on a stone, tiled, or concrete floor—not boarded. If this is not attainable, then let the mirror easel rest on a bracket bolted to the wall, and the table carrying the lamp be of the stoutest make, and stand on a hearthstone or some similar spot.

The quantities which the apparatus is designated to measure being of the order of millionths of an inch, no movement of the apparatus itself is tolerable.

A convenient form of support for the lamp and knife-edge is a very stout tripod table, with a small top made of soft pine board, planed nicely smooth. Its height should be such that a man kneeling at it can easily rest his elbows on it. It is advisable for the worker to make his own.

We have already seen what are the appearances presented by a spherical mirror when put to the question by the pinhole and knife-edge. But we shall rarely see a truly spherical one. Nearly always we shall have curves with a radius differing more or less in different parts. They will be either (1) radius longer in center than at edge (oblate spheroid), (2) radius very slightly shorter in center (ellipse or prolate spheroid), (3) radius a little shorter still in center (paraboloid) or (4) radius very much shorter in center (hyperboloid). Of these, (1) and (2), as well as the sphere, are under-corrected; (4) is over-corrected, and (3), the paraboloid, is truly corrected, and this is the curve which we desire to produce.

There are, of course, besides these an infinite variety of irregular figures, which may be combinations of any two or more of the above, or figures not

symmetrical, such as astigmatic curves produced by "flexure" (strain, or bending of the glass). The last is not likely to be met with if good glass of proper thickness is used and the directions already given as to mounting and holding it are followed. But if a disk of glass be cemented to a stout wooden block covering the whole of its back, as we have known some beginners do, it is pretty certain to be flexured; and a flexured mirror is rarely curable. The most usual irregularities are hills or hollows in the center, rings, and "turned-down edge." For the present it will only be necessary to be able to recognize the appearances presented by the principal types of regular figure, viz., oblate spheroid, sphere, paraboloid, and hyperboloid.

We have put the lamp on the left and knife-edge on the right, reversing the order of Francis, Wassell, and Draper, as a matter of convenience. It is most important that the knife-edge should be next the observer's right hand,* as very delicate movements of it have to be controlled. The lamp is never moved when testing. A little practice and thought on the cause of these phenomena will enable the beginner to distinguish a hill on his mirror from a hollow, even if the nature of the irregularity is not obvious at first sight.

The lamp used in these tests may be any small-flame one. A small Argand burner, with a narrow chimney, is perhaps the best. The smaller the source of light the nearer the knife-edge can approach the pinhole, and the less will be the *ecart* needed of pinhole and knife-edge from the actual optical axis of the mirror. They should not be too far from the axis, or distortion of the shadows will result; and, contrary to the opinion of many workers, the pinholes should not be too small. It is convenient to have two—one of liberal size, pierced with an ordinary sewing-needle, for rough-testing, and a small one, made with the point of a very fine needle, for fine work, eyepiece testing, and testing a mirror after silvering. We have known grotesque errors result from using too fine a hole. Indeed, on one occasion an absolutely perfect mirror was sent to the writer to correct for a "turned-down edge," which was entirely non-existent except in the owner's testing apparatus. He used an acetylene flame and an excessively tiny pinhole, with the result that he saw a series of diffraction bands inside the margin of his mirror, and took them for a turned-down edge. An eye-piece test will instantly detect a turned-down edge if any be present, even if too slight to notice with the knife-edge. But of this later.

It is convenient to cut two openings in our brass tube, opposite each other, cover the whole with a sliding collar of very thin sheet zinc, and pierce the holes in this, one in each opening. Lest the arrangement should collapse if the chimney should over-heat, it is perhaps well to avoid the use of solder, and to secure the zinc collar to the brass by means of a spring clip. A piece cut from a clock spring, of the requisite curve to encircle the tube, answers well.

Another way is to file the brass tube nearly through, and then pierce the thin remaining metal with a needle. But there is considerable advantage in being able to adjust the pinholes higher or lower in the tube, which, of course, is impossible if they are pierced in the metal of the tube itself.

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*See page 12.—Ed.

CHAPTER IV.

Polishing

Having provided ourselves with a Foucault's testing apparatus, we may now proceed to polish. The glass tool on which the mirror was ground is, with its wooden block, removed from the grinding barrel, thoroughly scrubbed and sluiced with water, to clean away all trace of abrasive, and transferred to the polishing barrel (and polishing room if we have one). Dry its fine-ground surface, and smear a little turps over it. Meanwhile a tin of pitch will be melting over the oil-stove. This should be carefully watched, and stirred frequently with a short stick.

It is a very great improvement to add to the pitch about 5 to 10 per cent. of beeswax. The effect of this will be appreciated when we come to cutting out the facets on the tool. Pure pitch is abominably sticky, and also is liable to fly into tiny chips when cut. These adhere to the skin, hair, and clothing, and are more than likely to conduce to profanity, being very difficult to get rid of. The wax-pitch mixture does not chip, and its stickiness is so much reduced that it can be molded with the fingers when soft without adhering. Still more important is what may be called its "flexibility," using the word in the motor-engineer's sense. Pure pitch, to work well, requires to be very close to the ideal degree of hardness. If it is too soft it very rapidly produces a deep hyperbola, and also a "turned edge," the dread of all the old mirror makers. If too hard it scratches. But the wax-pitch mixture will work well, within much wider limits of hardness, and seldom produces a turned edge.

It should be just possible to mark it with the thumb-nail when cold.

Watch that the pitch does not boil, and if it shows signs of doing so, lower the lamp. Prolonged heating hardens it. To soften, add carefully a little spirits of turpentine. (Do not spill any over the lamp, or there may be an explosion.) Not more than a teaspoonful should be added at once, as its effect is quite disproportionate to its quantity.

While the pitch is melting we get the mirror ready by standing it face up and painting it all over with a thin paste of rouge and water. We will require two or three glass jars (such as 1-lb jam jars) and a plate of glass to cover each to exclude dust, a camel's-hair brush, large and flat, and a knife, or, better still, an old razor. We also need a stamping tool. To make this, take a piece of nice cleanly-planed wood with straight faces about 9 in. x 1¼ in. x 2 in. Cut two pieces of thin hoop-iron 9 in. long, and file one edge of each to a wedge-shape. Clean both pieces up well with a file, drill three or four holes in each, and screw them to the sides of the piece of wood, so that their sharpened edges are parallel and 1¼ in. apart. This is our stamp for marking out the facets of the tool.

Mix in one of the jam-jars a tablespoonful of rouge with water to a thin cream, and paint some of it over the face of the mirror with the camel's-hair brush. When the pitch is quite liquid all through grasp the tin with a cloth, and pour it out rapidly on the tool, beginning at the edge, going inwards with

a spiral motion and ending at the center, where a considerable excess may be poured.

Lay the tin aside and at once take the mirror and press it face down on the semi-fluid mass, twisting it round and moving it to and fro for several minutes, or till the pitch is cool enough to retain its shape. It will overflow all around the tool. Let it stay there. It will do no harm and will safely imprison any bits of loose grit that may be present.

The layer of pitch on the face of the tool should be about $\frac{1}{8}$ in. deep, not more. When it is judged time, slide the mirror off, lay it aside, and take your stamp and press it lightly on the still soft tool. It leaves the impression of its two parallel edges. Lift it and place the second edge in the furrow of the first and press again. When you have gone across from side to side repeat the operation at right angles. The tool is now covered with systems of parallel lines, the two sets being at right angles to each other and dividing the surface into squares of $1\frac{1}{4}$ inch side.

Now we take the old razor and proceed to cut out V-shaped channels about $\frac{1}{8}$ in. wide along these lines. Cutting down to the glass, the strips cut out can be lifted clean out, leaving clear V-shaped furrows. We could not do this with pure pitch. We also get a criterion of the hardness. If the strips cut and lift out without either elongating or breaking up into bits, the hardness is just about right. A strip when cold should bend just a little before breaking. If it will bend nearly double without breaking it is too soft.

But there is one point about the facets which we have not mentioned, and it is an important one. The center of the tool must not be near the middle of a facet, nor must it be in a channel. It should be *in the corner* of a facet. If not, the mirror will polish in rings. It is a good plan to mark the center with a pair of compasses before using the stamp and then to stamp the lines embracing the center first.

The older workers, and especially Wassell, were very particular about the *shape* of the V-grooves, that the slope of the sides should be exactly 45 degrees. This, like too many of the older refinements, is pure bosh. It does not matter in the very least what the shape of the grooves is, provided they are hollow enough to give clear air channels under the face of the mirror. Nor does it matter what the shape of the facets is either. We only make them *square* because that is easiest. The $1\frac{1}{4}$ in. squares will do for all sizes of mirror from 6 in. to 10 in. Above 10 in. we may double the size and make them $2\frac{1}{2}$ in. Below 6 in. they may be dispensed with altogether.

The cutting of the facets will somewhat disturb the curve. As soon as it is finished, therefore, while the pitch is still a little soft, we must paint the tool over with the rouge and water, and place the mirror on and work it a bit, say for five to ten minutes, meanwhile observing through the glass what is happening. Probably at first the central facets will not be entirely in contact with the glass. We must work, if necessary, with pressure, till all air bubbles disappear and all facets are in contact. And here we find the advantage of having the back of the mirror transparent. We will find it again when silvering. Many makers grind the back; a foolish and a totally unnecessary proceeding. The only possible object of it is to prevent light which passes through

the silver film from being reflected from the back to illuminate the field of view. I have elsewhere shown that the maximum possible amount of light so returned could not exceed that of a 12th mag. star distributed over the entire field. So do not grind the back, and both figuring and silvering will benefit.

Now, having the tool in order, we proceed to polish. The motions are just the same as in fine-grinding. But now we must time ourselves. It is by time that we judge how much polishing the mirror has had. So a clock forms part of the furniture of the polishing-room. Another useful article is a thermometer, which should be hung not against the wall, but freely out in the room. A rise or fall of even 5 degrees in temperature will greatly affect the behavior of the tool. A rise softens the pitch and a fall hardens it; consequently, a change of temperature may quite alter the character and effect of our tool. For this reason, as well as for another, to be explained later on, a light building of wood or iron is totally unsuited for a polishing place. The best place of all is a cellar or basement below ground, where the temperature will remain reasonably constant. In any case it must be a building with substantial stone walls. And the sun should not be allowed to shine in if it has a large window. Especially it must not on any account shine on the tool, or we may have to remake the latter.

Having fully taken in these *caveats,* we may begin our first spell of polishing and go on for half an hour by the clock, using short strokes, and only stopping occasionally to renew the rouge and water. A dish of clean water, with a short stick having a large handful of absorbent cotton tied round one end, in it, will be found useful on the work-bench. This is to wash the rouge off the mirror when we stop to test, and keep our hands out of the mess. We also will need a few pieces of old linen, quite clean, for wiping the optical surface dry.

It is well to keep a written record of the spells of polishing and of the figure found at the end of each. At the end of the first spell the mirror should be semi-polished all over, rather more in the center. We may possibly find a very eccentric figure at this stage; perhaps a very exaggerated hyperbola. But do not mind. Go on, and it will come to reason later on. And if it does not, but gets worse, which is not likely, remember that any figure made by polishing can be unmade by polishing. It can never be necessary to regrind, no matter how eccentric the figure.

But it is more than likely that it will be found to be somewhere near a sphere. In any case go on. We are only polishing, not figuring, and have at least three hours' polishing before us before the figure matters at all.

The mirror should work easily, and smoothly on the tool. If it does not, but sticks and clings, the curves cannot be truly coincident. In this case it is useful to leave the mirror on the tool for several hours, with plenty of rouge and water between, to prevent sticking together, and three blocks of wood round to prevent sliding off.

After the first half-hour's polishing we may use the microscope to ascertain the prospects of quick polishing. A 1-in. objective is suitable. With this all pits and scratches are visible, and we can see if any deeper than the average are present. If none but the finest are visible we may expect to polish in

about three hours, or even less. The outer $\frac{1}{2}$-in. of the mirror is all that need be examined, as this zone is always the slowest in polishing.

If the successive stages of fine-grinding have not been done with sufficient thoroughness it will be quite easy with the microscope to identify the pits due to the successive grades of abrasive. Moreover, the appearance of emery pits is quite different from those due to carborundum. The latter are sharp-edged tiny holes, deeper than they are wide; those from emery are much more diffused, and naturally polish out quicker. Hence the advantage of an emery finish to the fine grinding.

We shadow-test, just for curiosity, before going on, for it is little likely that any errors gross enough to require a change of tool will be seen. Then we proceed to another half-hour's spell, and so on till the surface begins to look well polished to the naked eye.

During the preliminary polishing the water in the dish will be getting more and more stained with rouge. When it is no longer able to cleanse the mirror set the dish aside and take a clean one and a fresh lot of water. After the first dish has stood for twenty-four hours its charge of rouge will have settled. Pour off most of the water and with what is left rinse the dish round well, and pour off all but the last few drops into a clean 1-lb. glass jam jar, and put it aside covered with a glass plate. This will give us a reserve of extra-fine rouge for the final stages of figuring. This may be repeated as often as the water in the dish becomes too deeply stained to cleanse, and the fine rouge settled from the rinsings is most important in obtaining a surface clear of the tiny scratches rouge is apt to make.

Some samples of rouge are very scratchy, and cannot be used at all without treatment. They may be stirred up in a jar of water and poured off after $\frac{1}{4}$ to $\frac{1}{2}$ minute's settling. But a better plan is to make the rouge into a paste with water and then ladle the paste by spoonfuls into a flannel bag. Place this bag when full in a jar of water and knead it well under water. The fine powder comes through the bag and all coarse particles are left inside. It is a messy job, but worth while.

When we can no longer see any defect of polish with the naked eye we once more inquire of the microscope, and if no abrasive pits can be seen in the marginal zone of the mirror all is well so far as the polishing is concerned.

CHAPTER V.

Figuring

We now come to the *crux* of the whole process. Grinding and polishing are purely mechanical processes, which any handy man should be capable of learning in a few lessons. But the man who can produce a perfectly true paraboloidal curve right up to the edge of a mirror is not a mechanic, but an artist; and the artist is born, not made. Volumes might be written on the art of figuring, and the reader of them would be no nearer being able to produce a true curve after reading them than before, if the talent were not born in him.

Much depends on the figure which we find present at the completion of polishing. If it is a sphere, or an oblate spheroid, of a moderate amount of oblateness, and with no complications, such as turned-down edge, we may go ahead with the tool we have been using, taking to the fine rouge collected as described already. We have merely to deepen the curve very slightly towards the center. There are several ways of doing this. We may classify them:—

1. Parabolizing by long stroke.
2. Parabolizing by graduating facets.
3. The small polisher system.
4. Parabolizing by overhang.

The first two are old methods, and are described in all articles on the subject, from Herschel to Wassell, and later.

(1) Parabolizing by Long Stroke

We have been polishing in short strokes of about one-third diameter, and straight (center over center). If we now increase the *length* of stroke to one-half, two-thirds, or whole diameter, we shall get a more or less rapid hollowing of the central region of the mirror.

If there were no complications to this method, parabolizing would be easy; but, unfortunately, long stroke very often means producing a turned edge. It must, therefore, be used sparingly, and with discrimination. Supposing, for example, that the figure we have to parabolize is a sphere with a turned-*up* edge, we may use long strokes for a while, being careful not to overdo it. Dealing with an oblate spheroid in the same condition, we might use it a bit more freely. Resort must be had to Foucault's test at frequent intervals. But where there is a question of a turned-*down* edge we require a control on Foucault's test.

Very few mirror-workers are capable of detecting a turned edge by Foucault's test alone unless the turn-over is very gross. But an *eyepiece* test will decide the matter at once. For this we require an eyepiece of about one inch equivalent focus and a fitment to hold it which will stand in another ring of the retort-stand which carries our pinhole-lamp. To use it we simply remove the knife-edge out of the way, and slide the ring carrying the eyepiece down into its place till we can see in the latter the image of the pinhole. If the figure of the mirror is near a sphere the image will be nicely sharp. Now slide the whole stand, lamp, eyepiece and all, alternately nearer to, and further from,

the mirror, so that we get the image out of focus. If the image, when some distance inside focus, is a circular disk, with a clean, well-defined edge, the curve of the mirror is true to the very edge. But if the disk has a hairy, fuzzy, and ill-defined outline, the edge of the mirror has a flatter curve than the rest; in fact, it is "turned down." This test is infallible and extremely delicate for this one defect.

The expanded disk, outside focus, is *always* sharp in outline. Even when the mirror has a turned-up edge the appearance is not reversed, as we might

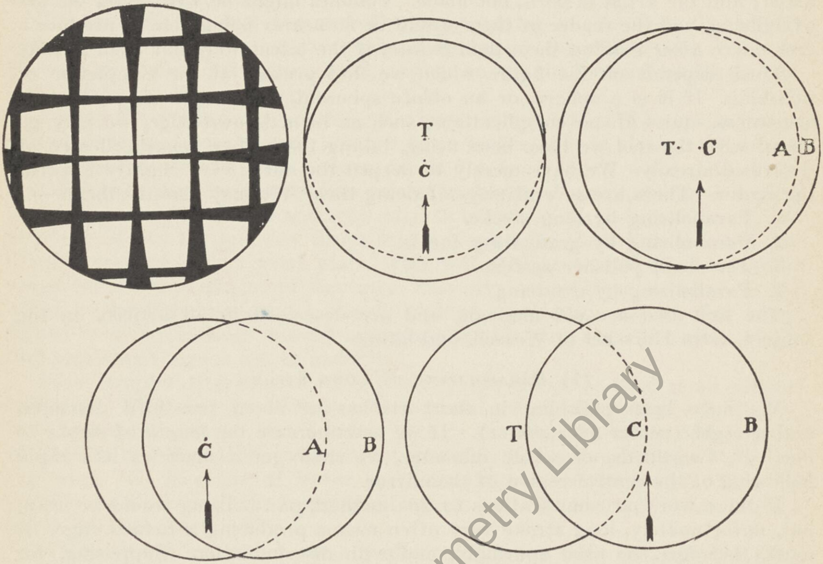

FIGURE 3

Upper left: Tool graduated for polishing. In each of the four remaining diagrams the complete circle represents the mirror and the arrow the direction in which its center, C, is moving to and fro. T is the center of the tool. In the first drawing, C passes over T at each stroke. In the second, third and fourth, C passes at greater and greater distances to the right of T, according to the effect required. In the last drawing the center of the mirror works on the edge of the tool. Not to be recommended unless central hill is to be removed, and then very cautiously.

suppose. In this case the outside-focus disk will have a slightly softer outline than usual, while the inside-focus one will be very sharp. In using this test, however, we must remember that the paraboloid which we are trying to produce is a figure which becomes flatter towards the edge. Therefore, we must not aim at getting the inside-focus disk too sharp. It should be just a little softer in outline than the outside-focus one when the mirror is finished. But a hairy edge to it cannot be tolerated.

The turned-down edge is the mirror maker's *bete noire*. Formerly it was considered impossible to escape it, and older makers used as a matter of

course to grind off the outer half-inch, or advise stopping the mirror down. But we know better now. As the "fatal hyperboloid" is now no longer incurable, neither is the almost equally dreaded turned-down edge.

(2) Parabolizing by Graduating Facets

This is the standard method of bringing an oblate spheroid or a sphere to a paraboloid. It seems obvious that if we reduce the size of the facets of our tool, progressively from center to edge, by widening the channels between them, we shall increase the amount of abrasion in the central parts relative to that near the edge, and thus will obtain the desired result of a deepened curve near the center, without increasing the stroke or imperilling the curve of the edge. The alteration will be made as shown in Figure 3, upper row, left.

This is, perhaps, the easiest method of graduation. It might also be done by leaving the middle facet as it is, trimming off the corners of the three nearest to it, and cutting those next in order down to circles, and yet smaller circles. This will often produce the desired effect, but not always. It is well to use a broad chisel and light wooden mallet for trimming facets and keep a large, soft brush handy for sweeping the tool free of chips. This should be kept in a dust-proof receptacle.

The above two methods of parabolizing are standard methods of all the old masters of the mirror-working art. Those that follow are the result of experiments of the present writer.

(3) The Small Polisher System

It has always been laid down as axiomatic that mirror and tool must be the same diameter; but, like many axioms of the old workers, this principle has no other foundation than their fear of attempting new methods. It is quite easy to both grind and polish on tools considerably smaller than the mirror. And what we have called the "Small Polisher System" is often useful as a remedy for the great enemy, "turned edge." A polisher a little less in diameter than the mirror, of hard pitch, used with short, straight strokes, will often remove a turned edge when everything else has failed. A polisher considerably less than the mirror, even so far as only two-thirds diameter, will rapidly hollow an obstinate oblate spheroid. Naturally, this requires to be used with caution, stopping every few minutes to test, lest a deep hyperbola result.

(4) Parabolizing by Overhang

Cutting and trimming the pitch tool is always more or less objectionable, if for no other reason than that it cannot be undone, once done, without the trouble of destroying the tool and making a fresh one. But without making any alteration in a satisfactory tool it can be made to cut the central region of the mirror faster as follows. Observe the four positions in Figure 3 (the figure at top left being excluded).

The first one shows the ordinary center over center stroke, with which we have been working. When the centers coincide, of mirror and tool, the weight of the mirror is equally supported all over by the tool.

But if instead of letting the center of the mirror pass over the center of the tool at each stroke, we bring the mirror a little to one side, as in the second, so that the crescent AB of the mirror is always off the tool, obviously the region of the mirror between C and A will be supporting the whole weight of the mirror, and will be pressed against the tool more forcibly than the rest of the surface. If, therefore, we polish with the mirror in this position, the mirror, as before, rotating about its center, and the worker walking round the barrel, we will get a greater abrasive effect in that part of the mirror, whose radius is CA.

And if we increase the overhang, as in the lower left, we further narrow the part of the mirror supporting its weight, and further concentrate the abrasion in the central region.

While if we place the mirror as in the last drawing of the group of four, with its center on the circumference of the tool, we get the whole pressure, due to the weight of the mirror, supported on its center alone. To work in this position would rapidly produce a deep hollow just in the center. It is therefore useful for removing a central hill, but it is not to be recommended except in such a case, and then very cautiously.

We have, therefore, in this method of "overhang" (so called because the mirror always overhangs the tool by a certain amount laterally during the entire stroke) a most valuable means of controlling the figure. It is obvious that we can work the overhang method with an elliptical or circular as well as with a straight stroke, and also that we can alternately increase and diminish the amount of overhang as we work. In this way we can distribute the extra abrasion due to overhang almost *ad libitum* over any required area about the center of the mirror, and therefore can probably produce a paraboloidal curve more easily by this method than by any other.

In all these operations it is well to have the back of the mirror protected from the heat of the hands by some non-conducting material. Otherwise a good deal of trouble may result, and the success of figuring may be considerably retarded. A piece of thick pasteboard cut to a circle the size of the mirror, and with the center cut out to admit the handle, will be found useful.

Working Uphill

So far we have been trying to bring the figure of our mirror from sphere to parabola, or from oblate spheroid to parabola, via sphere. Now this is the way that the figure of a mirror, if left to itself during polishing, will travel nine times out of ten. We therefore call it working "downhill."

But, supposing we have, to begin with, a more or less hyperboloidal figure, or that we have, in bringing the figure downhill by any of the above methods, overshot the mark, as very often happens, and obtained a hyperboloid, we will have to find means to make the curve retrace its steps. As this is considerably more difficult (it used to be counted impossible, hence the term "fatal hyperboloid"), we may call it "working uphill."

To begin with, we may lay down the principle that a hard polisher pulls the figure uphill, whereas a soft one lets it downhill. But we may as well say here at once that although various types of pitch polishers are calculated

to produce certain definite effects, the pitch tool is most delightfully inconsequential in its behavior, and one never knows for certain what any given tool will do till it is tried. It is as *varium et mutabile* as any woman, and a speculum maker may fancy that after some years of experience he has fathomed all that pitch can do when it will suddenly surprise him by some totally fresh whim.

However, the first thing to try, for a hyperbola as well as for a turned edge, is a hard tool and short strokes, and three times out of four this will be successful. If, however, it is not, we must try graduating the facets in the opposite way to that shown in Figure 3 (upper left) cutting down the central cnes and leaving the marginal ones full size. In extreme cases of a very deep or

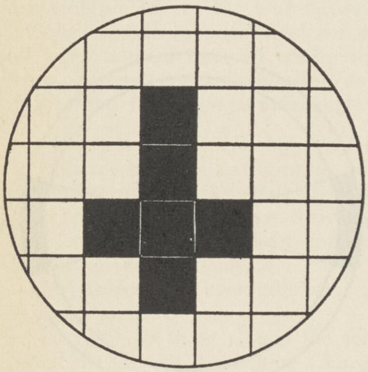

FIGURE 4

Facets shaved from the tool to reduce a hyperbolic figure.

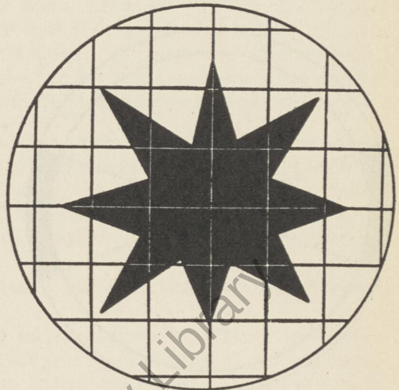

FIGURE 5

Another way to reduce a hyperbolic figure. This is more suitable than Fig. 4 for small sizes.

obstinate hyperbola the whole center of the tool may be removed bodily, leaving only a ring of pitch. This will probably result in an irregular oblate spheroid, whereupon we make a fresh tool, and proceed to work downhill again.

A shape which the writer often finds useful to bring a hyperbola to reason is an ordinary tool having a wide, rectangular strip the breadth of one, or even two, facets, removed right across the center, or having two such strips, one a facet longer than the other, crossing each other, as shown in Figure 4. It must not be supposed, of course, that this arrangement will produce a regular figure. It will probably result in a large hump in the center. When the center is sufficiently raised we can then make an ordinary "downhill" tool, and work towards a paraboloid again as before. If we have got, as sometimes happens, a figure, which is not exactly a hyperbola but has a big hollow in the center, the above tool, carefully used, may, with luck, bring it just right.

It sometimes happens that a ring, either raised or depressed, appears on the mirror. A polisher which rings the mirror probably has its center in the wrong place with respect to the facets. The ringing action may be reduced, or even entirely suppressed, by using an elliptical stroke, or "side," as it is sometimes called. "Side" tends to turn the edge, though not to the same extent as long stroke, and therefore should be used sparingly. A single depressed ring on an otherwise promising figure may be eliminated by cutting out two or three facets along the path of the ring, reducing the abrasion of that particular zone. A raised ring is more difficult to deal with. If not far from the circumference it may be removed by the "overhang" method, working so that the edge of the tool just traverses along the raised zone. It may also be dealt with by very cautious use of a polisher all cut away except a ring of

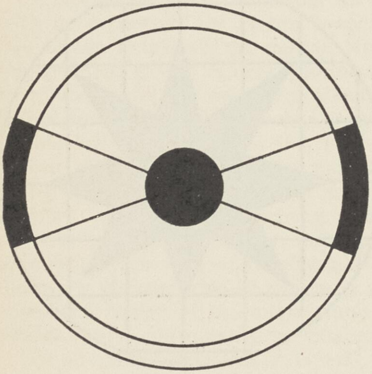

FIGURE 6

A cardboard stop for use in measuring the depth of parabolization. This style is termed Stop I.—ED.

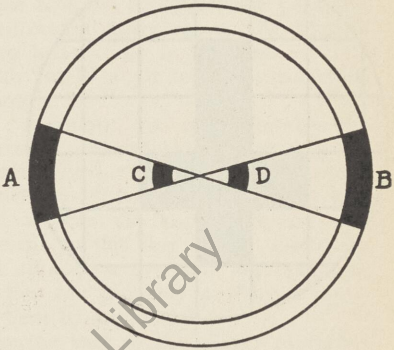

FIGURE 7

Another kind of stop, termed Stop II. The bottom of the stops may be shaped so that they will stand steadily.—ED.

the same size. A very few strokes at a time should be attempted on this, or we may get a depressed ring instead.

Having overcome these difficulties we will suppose we are now approaching the desired paraboloid. There are several difficulties of another kind to be met before we "get there."

If the worker be at all observant he will have noticed before this that the figure seen on testing immediately after removing the mirror from the tool is quite different from what appears some time later, when the mirror is allowed to rest awhile. The cause of this is, briefly, temperature. The friction of mirror on tool produces quite a considerable amount of heat, and we shall find that there is a very definite law connecting the figure of a mirror with its condition of temperature relative to the surrounding atmosphere. Briefly stated, the law is as follows:—

When a mirror is cooling its figure is temporarily pulled "downhill," or

in the direction of the hyperbola. When a mirror is warming its figure is temporarily pulled "uphill," or towards the sphere. (This, by the way, is the real reason why a slight under-correction is always given to specula by the best makers. A mirror, when in use on the heavens, is nearly always cooling slowly, with the atmosphere of a clear night. Consequently if its figure were a full paraboloid it would always, under working conditions, be a little over-corrected. To avoid this it is left a little under-corrected in the workshop.)

The result of this law is that we can never see the real figure of a mirror immediately after taking it off the tool. In fact, if we see a parabolic figure then, and leave it a while to cool, we shall find that it has changed to a sphere, or even an oblate spheroid. To obtain a paraboloid when cool we must have a very pronounced hyperboloid on taking it off the tool. At least half-an-hour must elapse before the true figure can be seen. Ignorance of this has caused endless trouble to beginners; for in order that the figure of a mirror may be all right it must look all wrong when just taken off the tool. Consequently, when approaching completion of our mirror, we have to pass through a period of working for a few minutes, and then waiting half-an-hour to see the result.

[Editor's Note: The apparent contradiction between the statements made in Ellison's last two paragraphs, above, has brought to the *Scientific American* a number of protests since the publication of the first edition of this book. Also the same apparent contradiction has led many British amateurs to protest in letters published by the magazine, *English Mechanics.* They accuse Ellison of inconsistency.

Yet there is no contradiction. Admittedly, however, the matter is difficult to grasp at first.

In reply to these claims the following letter written by Ellison was published in *English Mechanics* (April 30, 1926): "It is chang*ing,* not chang*ed,* temperature that has the effect I have so often described. A mirror which is truly corrected at 50° F. or 60° F., will also be truly corrected at 100° F., and equally truly corrected at 20° F. *It is during the process of changing from one temperature to another that its correction alters.*"

Bearing directly on this discussion, which became rather acrid during 1925-26 as letter after letter was contributed to *English Mechanics,* Professor Ritchey, the greatest living authority on mirror making, says: "The borders of the disk follow the variations of temperature more quickly than the center, and glass, a poor conductor of heat, is never quite the same temperature at all points. If the temperature rises, the borders warm up first and expand more than the remainder of the mirror. When the temperature falls the reverse becomes the case."

Occasionally, Ellison states, a disk will be found to perform in the reverse manner, but this is the exception that proves the rule and is due to some peculiarity in the individual piece of glass from which it was cut.]

CHAPTER VI.

How to Recognize the Paraboloid. Zonal Testing

The "Temperature Effect" is not the only difficulty to be encountered at the critical stage when we are nearly "there," but not quite. The question arises, "How are we to recognise the paraboloidal curve when we get it?" This is a very real difficulty. The only difference visible in testing between a true curve, one a little under, and one a little over-corrected, is a difference of *depth of shading.* We cannot leave this to mere personal judgment. We must have a means of distinguishing accurately. And this is the more necessary as the depth of shade in the parabola *varies enormously with the ratio of focal length to aperture.* The same shadows which would indicate a beautiful parabola in a mirror whose ratio was *f.* 8 (as the photographers conveniently call it) (*i. e.,* whose focal length was eight times its aperture) would mean a deep hyperbola in a mirror of *f.* 9. And when we get much beyond *f.* 10 or *f.* 11 we can *see no parabolic shadows at all.* If shadows can be seen in such a mirror it is hyperbolic. In other words, the difference between a sphere and a paraboloid in such a mirror is too small to be seen. It can, however, be measured.

We have already learned that when testing a spherical mirror, with the knife-edge just cutting the converging beam exactly at the centre of curvature, the mirror is seen to darken evenly all over. In other words, the difference of radius of curve for center and all zones distant from the center is zero. In the paraboloid and hyperboloid the radius of curvature increases outwards from the center. In the oblate spheroid it diminishes outwards.

Therefore, if we place over the mirror a stop which covers all its surface except a small area about the center, and adjust the knife-edge till this area darkens evenly, and then substitute for the first stop another which covers all except a strip of margin, if the mirror be a paraboloid we shall have to move the knife-edge a little way *further from* the mirror to get this marginal strip to darken evenly; and if it be a hyperboloid, a little further still.

And if we know *how much* the knife-edge must be moved back for a paraboloid we shall have an accurate means of recognizing the desired curve when we see it.

Now, the mathematicians have given us this information, and it is enshrined in the simple and easily remembered formula $\frac{r^2}{R}$ where r is the radius of the mirror, or of any zone thereof, which we desire to test, and R is its radius of curvature. For example, if we are testing a 6¼ in. mirror of 4 ft. focus (*i. e.,* 8 ft., or 96 in. radius), $\frac{r^2}{R} = \frac{3^2}{96} = \frac{9}{96} = 0.093$ in.

Therefore, if we find that, after adjusting the knife-edge to the radius of the center we have to move it back .093 in. (nearly 1-10 in.) to get the marginal zone to darken evenly, the mirror is a paraboloid, always provided that the mirror, tested without a stop, shows a *regular* curve, *i. e.,* is free from rings, hills, hollows, or turned edge.

Some workers prefer to test a whole series of zones, and tables are given of the values of $\frac{r^2}{R}$ for all diameters of zone and all focal lengths. It is, however, very trying to the eyes to test a long series of zones, and it is not necessary. For the open shadow test tells very clearly and unmistakably if the *general curve is regular.* And then it is only necessary to test the difference between the center and marginal zone, for if this is right and the curve is regular all the other zones *must* be right.

Now we can understand the object of the metal straight-edge attached to the stand of the knife-edge (see Figure 2, right). We pin a white card to the top of the testing table with a couple of thumb-tacks, stand the knife-edge on it, and when we get it adjusted for the center of the mirror, hold it firmly down, and draw a sharp-pointed pencil along the straight-edge.

Now we adjust for the marginal zone, and repeat the process, taking care to keep the block in which the knife-edge stands parallel to the edges of the card.

Now we have a pair of parallel lines on the card, and the distance between them will be $\frac{r^2}{R}$ if *our mirror is parabolic.*

Many and elaborate are the arrangements devised by Wassell and others for making this simple measurement. Micrometer-screw movements in two directions, springs to take up slack, scales, and microscopes to read them. The writer has tried them all, and ended by "chucking" them in favor of the simple method above described. The straight-edge, pencil, parallel lines on the card, and a pocket-lens and scale of 50ths of an inch, to measure the distance apart of the lines, are sufficient. The simpler a method is the better, provided it gives the desired result. And in all this little book the object before the writer has been to reduce everything to the maximum of simplicity consistent with efficiency.

The stops above referred to may conveniently be made of pasteboard. For each size of mirror two circular pieces may be cut, the exact size of the mirror. One has a circular hole cut in the center, a little larger than the minor axis of the flat which is to be used with the mirror, *e. g.*, for a 6¼ in. mirror a hole 1½ in. diameter will be suitable. From opposite sides of the margin two pieces are also cut, as shown in Figure 6. The shaded portions are those cut out. The width of the marginal zone may be ½ in. for mirrors of 4 to 5 ft. focus, but must be wider for ones of longer focus, owing to the greater distance from which it must be read. The other disk may be cut thus (Figure 7). The cross-lines and the inner circle are only for guidance in cutting.

The stops having been prepared, the mirror is placed on the easel, a card is pinned to the top of the testing table, and the knife-edge put in position and adjusted to the proper position for shadow testing. Care should be taken to place the straight-edge parallel to the sides of the card, and the sides of the latter parallel to those of the table.

The stop is now placed on the mirror. (The writer prefers stop I., but II. is the form most frequently used.) Let us suppose we are using No. II. What shall we see? Let us consider first zones A and B. As the knife-edge is

advanced across the beam of light, one of three things will happen. Either zone A darkens while B remains bright, or *vice versa,* or they both darken equally.

The observer must practise his judgment in deciding which of the two is the darker, as in reading a Bunsen's shadow photometer. If both are equally dark, the knife-edge is *at the focus of this zone,* and the pencil may be used to mark the position of the straight-edge.

Now *before moving the knife-edge,* observe the appearance of the zones C and D. If the mirror is parabolic or hyperbolic, the knife-edge when at the focus (center of curvature) of the zone A B will be *outside* the focus of zone C D, because in these curves the center has the shortest radius. Therefore, when A and B are *equally dark,* C will be *darker than D.* The knife-edge must therefore be moved *towards the mirror* a little to make C and D become equally dark. When they are judged equal, the pencil is used again. If the distance between the pencil lines is equal to $\frac{r^2}{R}$ the mirror is exactly corrected.

In practice it is always advisable, for the reason already stated, to leave the correction a little less than $\frac{r^2}{R}$ Thus in a mirror where $\frac{r^2}{R} = 0.10$ in. 0.08 in. would be a good correction. Even 0.06 in. might pass as sufficiently corrected. In any case a number of readings should be taken, and the mean of them all adopted as the true reading.

The chief difficulty the tester will meet with is the difficulty of deciding the exact point where C and D are equally dark. It is far easier to decide between A and B, owing to the more obtuse angle subtended by these at the center of curvature. Therefore, it is well to take a number of readings of C and D, sometimes taking the knife-edge well inside their focus and working outwards, and at other times well outside and working inwards. It is for this reason also that we recommend the stop of the form No. I., as it is somewhat easier to decide when the shadow in the central hole *travels neither way,* but comes on equally all over the hole, than to decide between the relative shades of the two slots C and D. If these slots are too narrow, the eye is very apt to be misled.

In the case of a long focus mirror, decision is naturally very difficult. Take, *e. g.,* a 6 in. of 6 ft. focus. In this case $\frac{r^2}{R} = \frac{7.29}{144} = 0.05$ in. Therefore 0.04 in. will be a good correction. The observer will find that when A and B are equally dark it will be difficult to decide that C and D are not equally dark also. In fact, 0.04 in. is a very usual margin of error between two readings of C and D, so that the real difference between the two pairs of zones is not greater than the possible error of observation.

Everyone who is accustomed to making delicate instrumental measurements knows how difficult it is to obtain a reliable reading under such circumstances. Therefore the mirror maker should beware of extreme focal lengths; *f.* 8 to *f.* 9 is the easiest for purposes of accurate correction. We have never yet seen a mirror of *f.* 10 and upwards, even by well-known makers, that was not over-corrected. Foci of *below f.* 8 are objectionable for another reason, though

when we get to apertures of 15 in. and above, considerations of space, weight of mountings, etc., make it necessary to adopt short foci. The trouble with these is that the wide-angle cone of rays upsets most eye-pieces, unless they are specially calculated for the purpose. Ordinary negative eyepieces give quite an unpleasant amount of false color on mirrors of *f.* 7 and *f.* 6, and really spoil the perfect achromatism of the reflector. Achromatic eyepieces should be used with all mirrors of focus below *f.* 8 if the finest definition is to be obtained.

In conclusion of this part of the subject, let us again repeat the warning given before with respect to temperature. It is absolutely necessary, the *sine qua non* of success, that testing shall be carried out in a place in which equilibrium of temperature can be maintained. The best of all places is a cellar completely underground, and free from draughts. If this is not available, the next best place is a basement room, partly underground. And if it must be above ground, it should be done in a substantial stone building, with as little window space as possible. It is *quite impossible* to get true readings in a living room, or any place artificially heated. It is equally impossible in a lightly-built workshop of timber or galvanized iron. In fact, such a building is hopeless for the mirror maker's work, except for the roughest parts of it.

Polishing, not to mention figuring or testing, is impossible in a place where the temperature may vary 20° or 30°, according as the day is sunny or cloudy. Testing *in the open air* is equally impossible. And this last is tantamount to saying that *testing on a star* is useless, for a star-test is necessarily in the open air. It sounds no doubt plausible to say that as a telescope is made for observing stars, its performance on a star must be the best criterion of its quality. But it is to be noted that this plea is used by those with the most limited experience of up-to-date methods of testing. And when we find that a star-test is capable of pronouncing *one and the same mirror on the same night by turns under-corrected, truly corrected, and over-corrected,* we see how little reliance is to be placed thereon. The writer has often had this experience when using various mirrors in the open air.

It is easy enough to see, by the out-of-focus images of a star, what is the state of correction of the mirror. A truly corrected mirror, out of focus, will give an expanded disk, uniformly illuminated except for faint traces of diffraction rings, having a clean, sharply defined edge, and a round black spot in the center. This black spot is the shadow of the flat, and it should be *the same size at equal distances inside and outside focus.*

If it is larger *inside* focus, the mirror is under-corrected. If it is larger *outside* focus, it is over-corrected. And many a time on a night when temperature was variable the writer has watched a mirror *change through all these phases* within not very many minutes, the changes of the black spot answering faithfully to those of the thermometer in the screen close by. And the changes are *not small.* A rise of 4° or 5° in the air temperature will instantly reduce the figure of the mirror from a true curve to a very much under-corrected one.

And such changes are frequent, especially on mild nights in autumn. The passage of a light cloud, the springing up of a breeze, the formation of a fog,

will raise air temperature suddenly by several degrees. And the mirror instantly responds by lowering its correction. And in the opposite event, of temperature falling sharply, the mirror goes the opposite way, the correction being raised. But this is less serious, because, as already pointed out, most mirrors are slightly under-corrected

The change, of course, is temporary, and is only due to the fact that, a mirror being a thick and massive piece of glass, and glass having a high heat capacity, its warming and cooling cannot keep pace with that of the air, but *lags behind it.* In point of fact, makers of specula, without knowing it, have been in the habit of *correcting them for a falling temperature.* If it were desired to use a speculum for daylight work, *e. g.,* for solar observation, it would be advisable to considerably over-correct, or in other words, to correct for a rising temperature. And in making a mirror for use in a climate such as that of Mexico, where temperature drops very rapidly after sunset, a figure in the neigborhood of a sphere might perform better than a paraboloid.

A striking illustration of this propensity of mirrors may here be mentioned. A 9-in. mirror made by Mr. Maurice A. Ainslie, a well-known and expert amateur speculum maker, was sent to the present writer for examination, and was found to be a little over-corrected. At the owner's request it was retouched, and the correction lowered. Some time afterwards the author was introduced to Mr. Ainslie at a meeting of the British Astronomical Association, and mentioned this mirror and its defective correction. It proved to be one which Mr. Ainslie had specially made for observing planets *in the morning twilight,* when temperature would be beginning to rise after the night, and was over-corrected because it was found to perform best in this condition.

It sometimes happens that a mirror is made of inferior glass or glass of unusual quality, and such mirrors will often have a whole set of peculiarities of their own. A thin mirror will sometimes perform quite well with one particular diameter vertical, but in all other positions give double images or reveal other signs of flexure. And twice within the writer's experience a mirror was submitted to him which *would not keep a figure.* A 9-in. mirror was on one occasion refigured *three times,* and on each occasion after a week or two was found very much under-corrected. At last the plan was adopted of strongly *over-correcting* it, and then the figure after a time came back to a paraboloid, *and stayed there.*

In concluding this part of the subject, let me give one caution to the beginner: *Do not be too ambitious.* A 6-in. mirror is quite large enough for a first essay. If not a success, as is more than probable, the loss is only a few shillings, and some time and labor. The difficulty of working a mirror increases by leaps and bounds with its aperture. Six-in. to 8-in. soon become fairly easy with some experience. But 12-in. is a tough proposition even for a skilled hand.

[The fraction $\frac{7.29}{144}$, on page 64 appears to be in error but is not. The square root of 7.29″ is 2.7″, the radius of the *center* of the zone, which is thus seen to be 0.6″ wide in this case.—Ed.]

CHAPTER VII.

Silvering

The mirror completed, it now only remains to provide its surface with its reflecting film of silver.

[See the directions for silvering issued by the U. S. Bureau of Standards, (Part III.) These are in some ways better suited to the American worker. The method chosen is especially recommended by Mr. R. W. Porter, author of Part I. After the omission of Ellison's directions for the actual silvering process, and the substitution of Part III for them, the text of the Ellison book continues below.—Ed.]

To Polish the Film

If we have hit off the right moment to remove the mirror from the silvering bath, very little polishing will be required. This is a great advantage, as there is always more or less risk of injuring the fragile skin of silver in polishing it. Make two pads of fine, soft chamois or washleather, stuffed tightly with absorbent cotton. Keep them in a clean jar or tin covered to exclude dust. One is to be used plain, the other covered with the very finest possible rouge. A regular speculum maker has no difficulty in obtaining the right stuff. With constant rubbing down on the tool a certain amount of rouge becomes so fine that it takes several days to settle out of suspension in water. When this is observed to be the case some of the red-stained water may be poured off into a glass dish and set aside in a warm, dry place, covered with a plate of glass. When observed to be settled clear, the water is poured off and some more of the same stuff added, and let settle in its turn. When enough sediment is seen to have collected let it remain till dry, always, of course, covered. The polishing pad is dipped in this, and takes a charge which will last almost *ad infinitum* without needing renewal.

If this method is not available we must put some dry rouge into a jar, fill up with water, and stir well. After settling, take on the finger-tip some of the red scum and froth which floats and smear it on a clean piece of glass. Dry carefully, and rub the polishing pad on it.

First rub the film carefully all over with the plain pad in small circular strokes. Then follow with the rouge pad. Very little of the latter will be needed if the mirror was not over-immersed. If it was, there will be a whitish film on it which will require a good deal of polishing to get rid of it. But even many hours' over-immersion will do no harm beyond a little extra trouble in polishing.

Once polished, leave the film quite alone. *Never attempt to get rid of tarnish by re-polishing.* You will lose far more light by *thinning* the film than you will gain by polishing it. Even when appearing very badly tarnished a silvered mirror retains nearly all its original light-grasp. Silvered glass, even at its best, never *looks* as bright as speculum metal. But appearances are deceptive. Silvered glass *looks dull* and *is* bright; speculum metal *looks bright* and *is* dull. When equally well polished a silver film reflects *about double* the light of a speculum metal surface the same size. Even when very badly tarnished, the silver film is still vastly superior to the metal at its best. This is a fact not always realized even by professional astronomers.

A Few Hints

Distilled Water.—It may not be easy to procure this in quantities sufficient for operating on a mirror of any size, but, unless one resides in a large town or near a manufacturing district, *clean rain-water* will answer all purposes if certain precautions are observed in collecting it. In the country rain-water off any clean roof will do. A glass roof is best; next best is a galvanized iron roof, and next a slated one without chimneys and free from moss and lichen. The best time to collect is on a very wet day after it has been raining for several hours. Do not dip the supply from a barrel or tank, but let it run from the eave-gutter direct into a clean vessel. Store a few gallons in clean corked bottles, replenishing the supply as occasion serves. Quart whiskey bottles answer well, as a trace of alcohol does no harm. If you are near the sea collect water only when the wind is *off the land.* Traces of chlorides are the most injurious impurities likely to be present, and they are sure to be there "when the wind bloweth in from the sea." Test a sample with a drop of silver nitrate. If no cloudiness forms in it the water is all right.

Care of Film

Next in importance to success in producing a film is success in keeping it. Two or three years are generally considered to be a good life for a film. But this can be very greatly extended, at least in the country, by suitable precautions in protecting the silvered surface. Its two enemies are *sulphur* and *moisture.* The first is only troublesome in a town atmosphere. A close-fitting cover, always on when the telescope is not in use, is the best remedy.

Moisture (the dewing of the mirror) cannot always be prevented unless the telescope is housed in a covered observatory. In the open air a rise in temperature of a few degrees, such as often happens on a fine night in autumn, will almost certainly dew the mirror. The only thing which can then be done is to close up the telescope and retire, especially as the rise of temperature will also upset the correction of the mirror for a time and play havoc with definition. But, short of a sudden rise of temperature, a mirror at the bottom of its tube, especially a wooden tube, is almost beyond the reach of dew. The flat *always* dews first.

The close-fitting cover, which every mirror should have, ought to be provided with an absorbent pad inside to take up moisture. I find the following plan so effective that I believe a film thus protected will last almost *ad infinitum,* certainly for very many years. Cut from stout pasteboard a circle large enough to fit loosely inside the mirror cell. Cut also similar circles from white blotting-paper and clean absorbent cotton. Make a sandwich of them, cardboard one side, blotting-paper the other, and absorbent cotton between, and stitch them together. Attach a loop of string to the pasteboard side. Before putting the cover on the mirror lay this pad on the face of mirror, blotting-paper next the surface of the glass, and put cover on over all. The string is for lifting off. If this pad be now and then well toasted before the fire or exposed to hot sunshine for an hour or two it will be dry enough to absorb all moisture within the cover and permit none to remain on the mirror. If the mirror ever gets dewed when

open, the pad placed on it for a few minutes will cause the dew to vanish completely. A similar pad is not without its uses inside the cover of an object-glass.

Protected in this way, I have had films in use for years and just as bright as the day they were deposited.

Residues.—In a workshop where much silvering is done it is worth while to preserve these. The mud left in the dish after silvering is *pure metallic silver* in a finely-divided condition. There is also a film on the bottom and sides of the vessel. Pour off as much of the liquid as possible without disturbing the sediment, fill up with water, and add a few drops of nitric acid. After standing for a few hours stir well, when the film will strip off in flakes, and the mud will collect in pellets, and the whole can be easily washed down into a large glass jar. Add a little solution of common salt to the contents of the jar to make sure that the silver is all precipitated. When enough has accumulated a wholesale chemist will purchase the contents of the jar for cash or give its equivalent in silver nitrate. In this way I have received as much as $\frac{1}{4}$-lb. of this valuable salt in exchange for quite a small jar of workshop residues. One saves at least three fourths of nitrate used.

CHAPTER VIII.

Mounting the Mirror

If we are to be particular, and want our mirror really finely mounted, the making of a suitable cell will be an engineering job, calling for a heavy iron casting and a powerful lathe to machine it—a job for a machine shop. But the Newtonian is a very tolerant instrument, and will perform well in a mount which the most unpretentious object-glass would disdain to be seen in.

Draper and With used to sling their mirrors in a simple leather strap, with a stout board for a backing, at the bottom of a square wooden tube. And though it is desirable to have something less rough and ready than this, we can provide a very excellent cell which will hold the mirror quite securely in adjustment and also protect it from moisture and tarnish when not in use with no more elaborate tool than the plain lathe aforesaid, a set of stocks and dies for screwing, and a few hand tools.

The first item required will be a thick disk of hard wood (oak is excellent), very slightly larger than the mirror and at least 1 in. thick; more if the mirror is 8 in. aperture or over. If a sufficiently thick piece cannot be obtained, get two, and screw and glue them together, with the grain crossed. The side on which the mirror is to rest should be faced up truly flat, or, better still, have a raised ring turned on it about three-quarters the diameter of the whole thing.

We next require a strip of sheet brass about 1 in. wider than the combined thickness of mirror and wooden disk; 1-16 in. sheet will do for a 6-in. to 8-in. mirror. For larger sizes it should be thicker. This is cut just long enough to go round the wooden disk and let the ends meet, but not overlap. Cut a strip about 1 in. wide and length equal to width of large strip, and sweat it on to the joined ends. Strip and ends should be tinned and well smeared with soldering flux. Then hold in hand-vise, ends meeting, and drill and put a couple of rivets through and tap up. Reverse vise, and repeat riveting at other end. Now solder the strip and ends. Now you have a joint that will not give way for a trifle. Slip the collar so formed over the wooden disk, drill half a dozen holes round into the wood, and insert screws, and there is your cell. It requires nothing more but means of attaching to telescope tube, something to keep mirror from falling out, and a cover-cap.

To keep the mirror in, we need not go to the trouble of fitting a rim. Three small blocks, cut out of ¼-in. sheet brass, will do. They should be spaced at intervals of 120 degrees round the inside of the cell, and either soldered to it, or, better, attached by drilling and tapping and putting a small counter-sunk screw through from outside. When thus attached, the mirror can be removed and replaced by merely unscrewing the blocks. If they are soldered, the screws holding the brass to the wood backing must be removed and the whole metal ring lifted off. As these are wood

screws, frequent removal is apt to make them loose in their holes. The method of attaching the blocks with screws is therefore to be preferred.

A simple method of attaching the cell to the tube is shown in Fig. 8. AB, CB, DB are pieces of flat iron or brass bar attached to the wooden back of the cell by screws as shown, and making angles of 120 degrees with each other. Each is long enough to extend considerably beyond the circumference of the cell, and the outer ends carry holes, the centers of which are at the angles of an equilateral triangle. These three holes fit over three screwed brass or iron rods, rigidly attached to the telescope tube. Each rod carries two nuts. One nut is placed on each rod and screwed up about ¾ in. Then the cell is slipped over the rods, the screwed ends entering the holes until stopped by the nuts. The second nut is then screwed on to each rod, and screwed home. Obviously, any desired adjustment can be obtained by slacking off one nut and tightening the other where required. The cover-cap merely requires a piece of sheet metal cut to a circle a little larger than the cell, and a strip of length equal to the circumference of the latter. The ends of this are joined, as described for the body of the cell, and it is soldered to the circular piece. It should be an easy fit for the cell, and to secure that it is a circle it should be slipped partly on to the cell, the latter inverted on to the piece of sheet and the strip soldered while in this position, taking care not to solder it to the cell itself. A piece of the same strip, bent to a suitable shape and soldered to the middle of the cover outside makes a handle for lifting off. The whole thing is much like the lid of a saucepan.

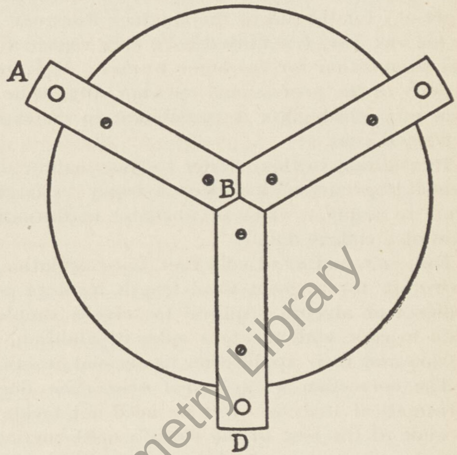

FIGURE 8

A simple method of attaching the cell to the tube—ED.

For a large cell, anything over 8 in., it is desirable to have the cover-cap convex. It can easily be made so by laying the circular sheet of metal on an anvil (failing one, the lathe bed will do) and tapping lightly all over with a hammer with a convex face. Begin in the center and go round in increasing circles to the circumference, repeating the operation till the desired degree of convexity is attained. Any spot which remains too flat should get a few extra taps of the hammer. If the sheet is brass this operation may make it brittle, and to prevent cracking it should be heated dull red, and then plunged in cold water, when it will be as soft as before hammering.

CHAPTER IX.*

The Achromatic Object-Glass

Notwithstanding all the merits of the reflector, its power, its magnificent capacity for definition, its colorless images, its compactness and economy of space, its simplicity and ease of manufacture, its cheapness, its comfort in use, there will always be a majority of the public to whom the word "telescope" means a refractor. And the refractor is certainly the most "fool-proof" form of the instrument. It has nothing about it which time can deteriorate, and its adjustments, once made, are permanent, barring accidents, meddling, or gross carelessness.

But, whereas there is an extensive literature in existence (however difficult to get at) for the aid of the amateur workman who desires to make a reflector for his own use, few indeed have ever regarded the achromatic lens as a practical proposition for the home worker. It is generally regarded as within the capacity of the professional optician only, while the high price of the necessary disks of optical glass is prohibitive to an experimenter, unless content with very small sizes.

In addition to this barrier to the amateur of limited means, the expression "calculating curves" has been a bogey to frighten away many a recruit. It seems to imply a vista of abstruse mathematical formulae, fit only for the brain of a college don.

But, as a matter of cold fact, the calculation of curves to correct *chromatic aberration* for a given focal length involves nothing more abstruse than the modicum of algebra required to solve a simple equation and sufficient arithmetic to cope with the four rules of addition, subtraction, multiplication and division and their application to decimal fractions.

The correction of *spherical aberration* does indeed call for complicated mathematical analysis. But we need not tackle it, for it has been done for us by some of the best of the world's mathematical brains, and all that we need do is to select one out of a small number of standard sets of curves. Even this is not absolutely necessary to the worker who has learned how to figure a curved surface, as will be seen later on. Now let us look the bogey in the face.

Calculating curves. First step.

The focal lengths of the lenses of crown and flint glass, respectively, which form an achromatic pair, must be proportional to their dispersive powers.

The makers of optical glasses give, with each piece supplied, an analysis of its "optical constants." These include its refractive index, its dispersion for various parts of the spectrum, and its "medium dispersion," that is, the dispersion of the whole spectrum between the lines C in the red end, and F in the blue-green. Also the reciprocal of the last named. These are the important figures. There are some others with which we need not concern ourselves.

* Revised for *Amateur Telescope Making* 1928, by the author.

The refractive index is usually designated by the Greek letter μ, the dispersion by Δ, and the reciprocal of the last by the letter V.

The example appended is taken from the catalogue of Messrs. Chance Bros., of Birmingham, England.

No.	Kind of Glass	Ref. Index for D.	Medium Dispersion C — F.	$V = \frac{\mu - 1}{\Delta}$	Partial Dispersion C — D	Partial Dispersion D — F	Sp. Gravity.
A605	Hard Crown.......	1.5175	0.00856	60.5	0.00252	0.00604	2.48
A569	Soft Crown........	1.5152	0.00906	56.9	0.00264	0.00642	2.55
A458	Light Flint........	1.5472	0.01196	45.8	0.00348	0.00848	2.93
A370	Dense Flint........	1.6124	0.01650	37.0	0.00474	0.01176	3.57
A360	Dense Flint........	1.6225	0.01729	36.0	0.00493	0.01236	3.66
A337	Extra Dense Flint.	1.6469	0.01917	33.7	0.00541	0.01376	3.88

The columns headed "Ref. Index for D," "Medium Dispersion" and

$$V = \frac{\mu - 1}{\Delta}$$

are the only ones with which we need concern ourselves. They will give us all that is required for an ordinary achromatic doublet lens. The letters C, D, F, etc., refer to the dark lines in the solar spectrum which are designated by these letters, and "Dispersion C — F" means that the figure given in this column is the dispersion between the C and F lines of the spectrum. As the C line is in the red, and the F line in the blue-green, the part of the spectrum most important to vision is included between these lines. When we use these in calculating an achromatic lens, in the finished lens the spectrum will be so folded back on itself as to *bring these lines together*. The result of this is that complementary colors are combined, and the combination produces white light. Since, however, the blue end of the spectrum extends considerably farther beyond F than the red does beyond C, the combination is not quite complete, and a little blue or violet light is left outstanding.

The spectrum is more dispersed at the violet end than at the red end. This "irrationality," as it is called, leaves a little violet light outside the correction, and consequently all "doublet" lenses have a "secondary spectrum," a slight purple halo being seen around the images of bright stars, and as a border to the disks of the planets. If, however, the lens is correctly worked, and the glass is of the most suitable kind, the secondary spectrum is quite unobtrusive. The best glasses show very little, even about the image of such a trying object as the planet Venus.

To get rid of the secondary spectrum we will need a triple lens and very special and expensive glasses. Such a lens is called "apochromatic," and is a very costly article indeed. I do not propose to treat of it. The amateur worker who succeeds in making a successful achromatic doublet is entitled to think himself a very excellent optician.

We may now proceed to plan an object-glass from glasses selected, either from the above list or elsewhere. It will be convenient to follow an actual operation. I select as example one of the first lenses I constructed. It was a

5-inch, and the materials were the dense flint A360 in the above list, and "optical Dutch plate." The Dutch plate was obtained from a London optical firm, because I had been struck by the excellent achromatism obtained by a combination of it with Chance's dense flint. The optical constants, as supplied by the makers, were as follows:

Optical plate:

Ref. index, 1.5195. Dispersion, C — F, 0.00906. V. 57.33

Dense flint:

Ref. index, 1.6230. Dispersion, C — F, 0.01730. V. 36.0

The crown was thus very similar to Chance's soft crown above, and the flint was their dense flint A360. The differences are no more than will usually be found in different meltings of the same composition of glass materials.

With every disk is supplied a paper stating the constants for that particular sample, which may be a little different from the list figures. The figures which we shall have to work with are the Ref. index, and those under V. The latter claim our attention first, for our first principle is that the focal lengths of our two lenses must be proportional to their dispersive powers. Now the dispersive power is found by the figure in the Ref. index column, *minus its integer 1,* being divided by the figure in the next column. The quotient is the figure in the V column. This quotient is not the dispersive power, but its reciprocal, and is used because the dispersive power is a very small fraction, while the reciprocal is a number of considerable magnitude, and so more convenient in the arithmetical processes to come.

For the benefit of non-mathematical readers we may explain that the reciprocal of a fraction is obtained by turning it upside down. That of an integer is a fraction of which the numerator is 1, while the denominator is the integer itself. Thus the reciprocal of three-eighths is eight-thirds; and that of 2 is ½, of 4, ¼, etc.

Now V, being the reciprocal of the dispersive power, is an inverse proportion, and the following is the relationship:

Focal length of crown : Focal length of flint :: V flint : V crown, the crown having the shorter focus. Or thus:

$$\frac{f,\,cr}{f,\,fl} = \frac{V,\,fl}{V,\,cr}$$

Now to express these in numbers:

We have above, crown V = 57.33. flint V = 36.0. Therefore, a lens composed of a convex crown of 36 inches focal length, and a concave flint of 57.33 inches, will be achromatic, if composed of these two afore-mentioned glasses. But the focal length of the combination will probably not be what we require. Let us see what it will be.

The formula for focal length of a series of lenses in contact is

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3} + \text{etc.},$$

if all are positive or all negative.

If some are one and some the other it becomes

$$\frac{1}{F} = \frac{1}{f_1} - \frac{1}{f_2} + \frac{1}{f_3} \text{ etc.,}$$

the concaves being negative and the convexes positive. If there is a space d between any of them, then it becomes

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2 - d_1} + \frac{1}{f_3 - d_2} \text{ etc.}$$

Now we can obtain from the above the means of ascertaining the focal length of our combination of a convex of 36 inches, and a concave of 57.33 inches.

$$\frac{1}{36} = .02777$$

$$\frac{1}{57.33} = .01744$$

$$\text{Difference} = .01033$$

$\frac{1}{.01033} = 96.8$ inches, the required focal length.

Or thus:

$$\frac{1}{36} - \frac{1}{57.33} = \frac{57.33 - 36}{57.33 \times 36} = \frac{21.33}{2063.88}.$$

Reciprocal of this, $\frac{2063.88}{21.33} = 97.2$ inches.

The apparent discrepancy if 0.4 inch between the two results is due to our having limited the decimals in the first operation to five places. The second result, obtained by vulgar fractions, is the more accurate, though the difference is quite unimportant. We may take 97 as a sufficiently accurate result, and avoid some fractions, which will not matter. Now our answer, 97 inches, would suit a 6-inch, or 6½-inch lens very well, but would be inconveniently long for a 5-inch, for which we want about 75 inches. A simple sum in "rule of three" will now give us what we want.

97 : 75 :: 36 : 27.8 crown focus.
97 : 75 :: 57.33 : 44.22 flint focus.

We have now reached the conclusion of the first step in our calculation of curves. We have ascertained that our convex crown lens must have a focal length of 27.8 inches, and our concave flint a negative focal length of 44.22 inches, in order that the focal length of the combination may be 75 inches. We have also ascertained that the combination will be achromatic, if composed of those glasses with whose optical constants we have been dealing.

To produce an achromatic combination from two glasses taken from makers' lists, look to the column headed V. Let the focal lengths be inversely proportional to the figures opposite the respective glasses in that column.

N. B.—To avoid trouble it may here be stated that the heading of the fifth

column in the glass makers' table of constants is often misprinted. It should be, as stated above:

$$V = \frac{\mu - 1}{\Delta}$$

But Greek letters are not always to be found in a printer's font of type, and very seldom in a commercial typewriter, so various substitutes for them are frequently used, such as n for μ and D for the mathematician's Δ.

Let me again call the reader's attention to the fact that *reciprocals* are used throughout the calculations. It is not F that is the significant figure but $\frac{1}{F}$, etc.

We now proceed to the *Second Step* in the process. We have ascertained the focal lengths required. Now we want to know to what curves we must work our two glasses, in order to obtain these focal lengths. We also want to know how to provide for the elimination of *spherical aberration.*

As already stated, the latter condition is secured by adopting one or other of a few standard sets of curves, which are well known and used by all opticians. In 1915 the National Physical Laboratory published a book of *data* for object-glass construction containing suitable curves for all Chance Bros.' glasses. (Harrison & Sons, St. Martin's Lane, London, W.C.) The worker has, therefore, only to make his selection. One will naturally choose those which promise to be easiest to work and test. Two, or three at the most, will suffice for our purposes.

(I.) Crown lens: Radii of surfaces as 2 : 3.

Flint lens: One surface fits one surface of crown. The other is a plane, or a concave or convex of long radius (very nearly plane).

This gives a choice of two forms for the flint lens. If it is made to fit the shallower curve of the crown, its other surface will usually need to be another concave. If it fits the deeper curve, it probably needs a convex on its other surface. These two alternatives may be described as two different sets of curves, and they have slightly different properties, the latter giving a larger and flatter field of view, for which reason it is preferred for photographic lenses. The former is somewhat easier to construct.

(II.) Crown lens an equi-convex.

Flint lens plano-concave. Its concave surface has the same radius as either surface of the crown.

We have, therefore, three equal curves and one plane surface. This is a favorite set with many of the great telescope makers, such as Grubb, and Cooke. The only snag in it is the plane surface, as planes are more difficult to produce perfect than curves.

Messrs. Chance Bros. have a special pair of glasses which will give perfect achromatism with any three equal curves and a plane, one of the curves being the concave of the flint. These are their "Telescope Crown," 3289, and Dense Flint, Type 361. The optical constants of these are, respectively:

Crown Ref. index, 1.5153. Mean dispersion, .00858. V. 60.0.

Flint Ref. index, 1.6214. Mean dispersion, .01724. V. 36.1.

These are very simple figures to work with. The crown also being equi-convex, and the flint having only one curved surface, the calculations are reduced to a minimum; so that, except for the difficulties of the plane surface, the second set of curves is the most suitable for the amateur worker to attempt. We will return to it later on.

At present we are engaged on the 5-inch optical plate and dense flint, and have ascertained that the crown lens is to have a focal length of 27.8 inches, with radii of the surfaces in the ratio of 2 : 3.

The formula connecting curves with focal length is:

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

But in the present case $\frac{r_1}{r_2} = \frac{2}{3}$ so that $3r_1 = 2r_2$

therefore $\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$ becomes $\frac{5}{2r_2}$ and we have

$$\frac{1}{f} = (\mu - 1)\,\frac{5}{2r_2} = \frac{5\,(\mu - 1)}{2r_2}$$

Substituting for f and μ their values, which we know (27.8 and 1.5195), we have

$\frac{1}{27.8} = \frac{.5195 \times 5}{2r_2} = \frac{2.5975}{2r_2}$ therefore $27.8 = \frac{2r_2}{2.5975}$ and $2r_2 = 27.8 \times 2.5975 = 72.21$.

r_2 therefore $= 36.1$ inches. But r_1 is two-thirds of r_2, therefore $r_1 = 24.06$ inches.

The radii of the curves of our crown lens are therefore 36.1 and 24.06 inches, respectively.

For the flint we proceed in the same way. But we have one of its curves already, as it is to fit the crown. This is not necessary, but very convenient, and may be labor-saving, for we can grind one glass with the other, and thus form two curves at once.

If we make the flint concave to fit the deeper side of the crown, we shall find (with a flint of such density as we are using) that the other surface will have to be a convex, as noted above in treating of the second modification of the first set of curves. This would make an excellent lens, but it would involve the treatment of *three* convex surfaces. We can test a concave by the shadow method, but not a convex, and as our present object is to make the process as simple as possible, we take the shallower curve of the crown to fit the flint. The first surface of the flint is therefore to have a concave curve of 36 inches radius. What must the other be?

The formula is as before:

$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$. The focal length is to be 44.22 inches.

Substituting

$$\frac{1}{44.22} = .623\left(\frac{1}{r} + \frac{1}{36}\right) = \frac{.623\ (36 + r)}{36r}$$

Therefore $36r = 44.22 \times .623\ (36 + r) = 27.55\ (36 + r) = 991.8 + {}^{*}27.55r$ and $36r - 27.55r = 8.45r = 991.8.$

$r = \frac{991.8}{8.45} = 117.3$ inches. This is the radius of the fourth surface.

We can now write down the complete specification for our 5-inch object-glass.

Crown lens	1st surface,	24 inches	convex.
	2nd surface,	36 inches	convex.
Flint lens	3rd surface,	36 inches	concave.
	4th surface,	117 inches	concave.

Crown focus, 27.88 inches
Flint focus, 44.22 inches } Combination focus = 75 inches.

We have neglected the decimals in the radii because they are so small that they could hardly be given effect in practical working. There is also another reason, viz., that the above formulae are only exact for the theoretical case of a lens *of no thickness.* The thickness introduces a small error, by making the crown lens weaker (of longer focus) than computed. It has no effect on a lens with one plane surface, and therefore the flint lens, being nearly plano-concave, is left unaffected. The net result is to make the finished lens, *if worked exactly as computed,* slightly over-corrected for color. The *if,* however, is a big one; and, all things considered, it is better to get as near to the computed curves as our skill will enable us.

For such lenses as we are working with, where the focal length is about 100 times the thickness, the error is very small. It is troublesome to correct for thickness, and opticians commonly neglect the small error. Many lenses made by the big makers are a little over-corrected in consequence. Others are remedied by mounting the lenses, not in contact, but separated by a distance ring. This separation has the effect of lowering the color correction, and the thickness of the ring can be adjusted till the correction is perfect. For terrestrial and look-out purposes a slightly over-corrected lens works well, for the erecting eyepiece usually employed is under-corrected and compensates the object-glass.

We will now glance briefly at the other set of curves given above, for Chance's Telescope Crown, and Dense Flint Type 361.

As stated, these give perfect correction with three curved surfaces of equal radii, and one plane. The writer constructed several object-glasses with these

* Note: If this figure is greater than the coefficient of r on the left of the equation, at the next step this term will become *negative.* This will signify that the curve of the fourth surface will be of opposite sign to the third; i. e., in this case *convex.* If the coefficients come out equal, it will be plane.

some five years ago, and found them answer admirably. Two of these were glasses of 6 inches aperture, and 91 inches focus, and this is a very convenient size to take as an example.

Let us consider how the formula for focal length will work out.

The constants are:

Telescope Crown. R. index, 1.5153. V. 60.0.
Dense Flint 361. R. index, 1.6214. V. 36.1.

By the principle used in our first step above, a convex crown of 36.1-inch focus, and a concave flint of 60-inch focus, made of these glasses, will be achromatic. Its focal length, too, will be somewhere near 90 inches, which will do well for a 6-inch.

$$\frac{1}{36} - \frac{1}{60} = \frac{60-36}{60 \times 36} = \frac{24}{2160}$$

Reciprocal $\frac{2160}{24} = 90$ inches.

Having neglected the decimal .1 for the sake of simplicity in calculation, our crown lens will be a little too strong. It will therefore do no harm to allow a little for this, or else do the calculation again, using the amended figure, 36.1. But it is quite possible that the actual glasses supplied may differ slightly from the list constants; so we will leave it at that. The fault is on the right side in any case.

Now let us have the old formula again: $\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$

But since r_1 and r_2 are this time equal, it becomes $\frac{1}{f} = (\mu - 1)\frac{2}{r} = \frac{2(\mu - 1)}{r}$

Now if $\mu = 1.5$, then $\mu - 1 = 0.5$ or ½, and $\frac{2(\mu - 1)}{r} = \frac{1}{r}$.

So $\frac{1}{f} = \frac{1}{r}$ and $f = r$. Hence an equiconvex lens made of glass with a reference index of 1.5 has a focal length equal to the radius of either surface. A plano-convex lens of the same glass has a focal length equal to twice its radius. This is useful to remember. Our telescope crown, however, has a reference index slightly greater than 1.5. In this case $\mu - 1$ will be 0.5153, and twice this is 1.0306.

So $\frac{1}{f} = \frac{1.0306}{r}$ and $f = \frac{r}{1.0306} = \frac{36}{1.0306} = 34.93$, or very nearly 35 inches.

In the case of the flint lens there is only one curve.

So $\frac{1}{f} = \frac{\mu - 1}{r} = \frac{.6214}{r}$ and $f = \frac{\mathrm{r}}{.6214} = \frac{36.1}{.6214} = 58.9$.

Though these results do not look like mathematical accuracy, they are near enough for our purpose. The reason of their seeming roughness is that the figures given for V are approximations to one decimal place. The crown V above, for example, is 60.06. 60.0 is the makers' round number, which is near

enough to work to. In working the same glasses I used 36 inches as my standard, and getting as near it as was practicable, I obtained excellent results, the combined focal length working out at 91.5 inches.

The equiconvex crown has some important advantages, both in working and use. It can be reversed without detriment to its spherical correction, if properly figured. For the optician, who uses cast-iron or brass tools, it has the advantage of requiring only one set of tools for the two surfaces. And it would be quite possible, with this set of curves, to *dispense altogether with calculation,* and work to the V figures; giving the crown two surfaces of 36 inches radius, and the flint one. This would give a lens of 90-inch focus, and would be very fairly well corrected for color. If not quite satisfactory, it could be separated a little if over-corrected, or the fourth surface given a *very* slight concavity, if under-corrected. The dimensions above would be right for a 6-inch. For a 3-inch the figures could be halved; and for other apertures in proportion.

Lest the testing of the plane surface should be a difficulty, refer to Figure 10. Here the simple set-up quite clearly shows the method of testing an object-glass by means of a perfect plane. Obviously, a plane can be tested by means of a perfect object-glass in the same manner. For the optician who has many object-glasses to work, a true optical plane of considerable size is a necessity. The amateur who cannot obtain one is advised to confine his attention to set of curves No. (I).

It may not be amiss to note here that, in all ordinary object-glasses, the crown lens always "leads," that is, it is nearest to the object, or is the outer glass in a telescope. A few German opticians put the flint lens leading, but this requires a reconstruction of the whole scheme of curves. British and American glasses have the crown the outer. It is rather a peculiar circumstance that seamen seem to have a preference for turning the flat side of their glasses out. The writer has examined numerous "spy-glasses," at coast-guard and life-boat stations and elsewhere, and always has found their object-glasses wrong side out. Needless to say, the effect on their performance is anything but beneficial.

The surfaces of an object-glass are always numbered from the front curve backwards; first, second, third, fourth; the first being the outer. In the case of a triplet there would be a fifth and sixth.

CHAPTER X.

Practical—Shaping and Grinding

It will not be necessary to recapitulate the processes of coarse and fine grinding, which have already been described in dealing with speculum making. Everyone who has made a concave mirror is already familiar with the production of concave and convex spherical surfaces by grinding two equal plane disks of glass upon each other. The same process which produces the shallow curves of telescopic specula need only be carried a little further to produce the deeper curves of an object-glass. There is only one important difference, viz., that now we have to produce curved surfaces *on both sides* of a disk of glass, and these surfaces must be correctly centered with respect to each other. In other words, the edge of the lens must be exactly the *same thickness all round.* To secure this we require a pair of *micrometer calipers.* The ordinary calipers are not at all delicate enough for the extreme accuracy required. An error of 1/1,000 inch in the thickness of the edge will produce a most deleterious effect on the images produced by the finished lens.

The optical glass we require is sold either in disks or in square slabs. In the latter form it is considerably cheaper, but we have the trouble of cutting out the disks. This operation is not so difficult as it looks. The corners of a square slab of glass are quite easily sawn off with a piece of hoop-iron and a little No. 80 or 120 carborundum and water. The saw-cut is begun on one side and carried nearly half-way through, then begun again on the other side, and when the cuts have come near enough the corner is gripped in the vice and broken off. In this way the square is made an octagon. The angles of the octagon can then be further blunted with the carborundum wheel or grindstone, and finally the piece is cemented with pitch to a pair of wooden handles mounted in the lathe and edged circular, and reduced to the required diameter in the same way in which the disk for a mirror is edged, that is, with a band of hoop-iron attached at one end and bent up for a handle at the other, the band nearly encircling the disk; and using No. 80 carbo. followed by finer sizes.

Two disks, the crown and flint, will, of course, be prepared, and these must be of *absolutely exactly* the same diameter. It is a good plan to cement them together and edge both at the one operation. But care is necessary not to damage them in parting them again. Also, the edges should be bevelled as a precaution against chipping by accidental blows. Two or three disks of ordinary plate glass ¾ inch thick or thereabouts should be edged also to the same diameter, to serve as tools.

If it has been decided that the second and third surfaces, being of the same radius, shall be made to grind each other, thus saving one whole operation of rough and fine grinding, we now cement the crown disk to a thick disk of wood, as we would the glass tool for a mirror, but with this difference, that the block should be of considerably smaller diameter than the glass, about two-thirds of it, and it is provided with a disk of sheet-iron of a diameter a little greater than the glass, which is screwed to the wooden disk concentrically for attachment to the barrel. The glass is, of course, cemented with pitch and

the sheet-iron is attached to the top of the now familiar barrel by means of screws. The object of the arrangement is twofold. The crown disk is not very thick, and if attached to a bed of pitch covering its whole surface would infallibly be flexured. And later on, when the other side of the crown is being ground, it will be necessary to have *room on both sides* of it to admit the micrometer calipers to gauge the thickness of the edge.

We are now ready to commence operations, and having provided the flint disk with a wooden handle, as we do a mirror, and placed a basin of water and a handful of absorbent cotton handy on the work-bench, we proceed to arm the disks with a sprinkling of No. 80 carborundum, dip the flint in the water, lay it on the crown, and grind with the mirror-maker's threefold motion.

It is to be noted that the handle by which the flint is held should be carefully centered. This is not absolutely necessary in grinding a mirror, but essential in making a lens whose two surfaces have to work with each other. About two or three hours, according to the size of the disk, will probably suffice to bring the curve near the required depth. As the grinding progresses the curve is checked from time to time, as in the case of a mirror, by wetting the concave surface and testing it with a light. (See Chapter II).

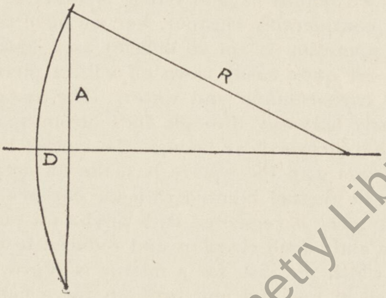

FIGURE 9

The radius $R=\frac{A^2+D^2}{2D}$

It is necessary to stop the rough grinding while the curve is still a foot or more longer in radius than we require. Carefully clean the disks and barrel of all trace of the rough carborundum, throw away the absorbent cotton and water in the basin, and get a fresh lot, and proceed to the next carborundum grade, 220. With this the curve is brought very nearly to the exact depth required. To gauge its progress more exactly than with the candle flame, we now use the modification of Foucault's pin-hole lamp, which we used for testing mirrors at the same stage. Opticians use a spherometer to read the curve of spherical surfaces. This is a small instrument with three feet, either pointed or ball-tipped; the three occupying the angles of an equilateral triangle. In the center is a fine micrometer screw, with a point which can be screwed down to touch the surface on which the feet rest. The radius of the curve as obtained from its reading, is shown in Figure 9.

The reading of the micrometer screw gives D, and A is the distance from the screw point to each foot. The spherometer is an expensive little instrument if accurately made, and the method described above of obtaining the radius of a concave curve is just as accurate in practice, if not more so. To measure a convex we measure the concave tool which ground it, and as the fit of the two at the end of fine grinding is very exact the method is quite satisfactory.

The directions for fine grinding given in the section on mirror-working are in no respect different from the methods to be used with a lens, and they need not be here repeated. The only difference is that, as the convex tool in this case is the crown lens itself, it is not advisable to use it to form the pitch tool or for polishing the corresponding concave. Any old glass tool of approximately the same curve and size can be used, or, failing a suitable one, a disk of hard wood can be turned up to near the curve, and the pitch tool formed on that. But it is well to postpone polishing any surface till all are fine-ground.

Having finished fine-grinding the second and third surfaces on each other, we now proceed to rough out the first surface. The crown is detached from its block, turned over, and re-cemented flat side up. One of the pieces of plate glass prepared for a tool is cemented to a handle, and the process goes on as before. But this time we must bring the *micro-calipers* into play. As the curve approaches the desired depth (ascertained by measuring that of the tool) we must try the calipers round the edge of the lens at frequent intervals. If any part of the circumference shows excess of thickness it must be reduced by temporarily stopping the operator's walk around the barrel and working with increased pressure on the thickest part for a few minutes at a time till the calipers show equality all round. Of course, before applying the calipers the lens must be washed and dried. No grit must be present, and a wet surface is very undesirable.

As the *thickness* of the lens enters into the formula for focal length, it will be necessary to pay attention to this point. One-half inch is a convenient thickness for a 5-inch to 6-inch lens (crown). If the slab to begin with is just a little more than this, it will come very nearly right when finished. If not, perhaps the simplest way will be to compute the curves at first for a thickness a little less than that of the slab. Otherwise it may be necessary to grind with very short strokes, in order to prevent the curve reaching the desired depth before the thickness is sufficiently reduced, which would waste a lot of time and labor.

When the fine-grinding of the first surface is complete, we turn to the fourth surface. As this is a shallow curve, working it resembles in every respect the making of a mirror, except that the micro-calipers must be busy checking the exact equality of thickness all round the edge. The handle (cemented to the center of the third surface) must be carefully centered. Grip it in a three-jaw chuck in the lathe, and rotate it and the disk while the pitch is still soft, and correct any lack of truth in its running by pressure in the direction required. It will be nearly impossible to keep the third and fourth surfaces truly centered with respect to each other if this handle is not in the center of its disk. When completed, or better, just before the last stage or

two of fine-grinding, it will be well to see that the bevel placed on both disks is not ground entirely off. If it is it should be restored, or an ugly chip may result from any slight accidental jar.

Polishing

Once more the mirror-maker finds himself on familiar ground, with some differences. The pitch polishing tool is formed, just as in the case of a mirror. It is, however, less necessary to be careful about the facetting. For sizes of 4 inches and under it is not necessary to facet at all, or two channels at right angles to each other, dividing the tool into four unequal parts will be sufficient. Above 5 inches the tool may be divided into squares of $1\frac{1}{4}$-inch side, the center of tool being in the corner of a square, precisely as is done when preparing a polishing tool for a mirror.

The convex surfaces of the crown lens may conveniently be polished first. No question of their figure can arise at this stage of the proceedings, as it is impossible to test it. It will, however, be advisable to use a pitch tool well on the hard side to avoid "turned edge," which is just as formidable in a lens as in a mirror. Also it will do no harm to cut away a little of the center of the tool, preferably in the shape of a star; as in polishing a convex the center is apt to get more than its share, with the result of flattening the curve there. It is no harm at all if a hump in the center is the result, as it is very easily removed later on.

The polishing should be continued till no abrasive marks are visible on examining the edge of the lens with a microscope. Nearly all makers scamp their polishing more or less. It is a rare thing to find a lens, even by the great masters of the art, one or more surfaces of which do not show, when examined with a low power on the microscope, thousands of tiny abrasive pits. Each of these is in practice a minute opaque spot, and the presence of thousands of them has two results, both bad for the performance of the lens. It reduces the transparency, and consequently the light-grasp. And it introduces diffraction effects which scatter light and illuminate the background of the field of view.

The crown lens may be polished either face up or face down. Face down is probably preferable, as the small handle cemented to the glass for holding by, is more easily detached and refixed without danger, than the block underneath would be, and there is less risk of flexure.

It must always be borne in mind that the crown lens is the thinner of the two, and not half the thickness, relative to its diameter, that a mirror would have. Fortunately, flexure must be much greater, to affect perceptibly the performance, in a lens than in a mirror. The reason is that if a lens is flexured, the two sides are bent *opposite ways.* Consequently, the flexure of one side compensates that of the other. Sir H. Grubb has shown that in the theoretical case of a lens with no thickness, flexure, however great, would have no effect, for the compensation of one side by the other would be complete. As our lens, however, must have a thickness we must see that flexure is avoided as far as possible.

Having polished the convex surfaces, we now proceed to the more familiar task of polishing the concaves. The third surface, the deeper concave, should be done first. Its figure can be roughly checked by the shadow test, though, owing to its short radius, it is impossible to test it with delicacy because the image of the pin-hole must be thrown far enough from the optical axis to distort the shadow very appreciably if it is to be brought within reach of examination. But it can be tested well enough to ascertain that its figure does not depart very markedly from a sphere.

The fourth surface can be polished and figured usually just like a mirror. But we need not strive after any definite figure at present. It will suffice to see that it does not become a deep hyperbola. It is best to have it somewhere near a sphere. If it should by chance turn out to be a pronounced oblate spheroid, let it remain so, as the final correction will be all the easier. But do not tolerate any irregularities. Humps or hollows in the center, or a turned down edge, should be eliminated as carefully as from a mirror, especially the hollows.

CHAPTER XI.

Testing and Figuring

When the polish of the four surfaces is complete the lens can be assembled and tested for focal length. If the curves have been worked accurately as computed, this should come out very close to the computed focus. But if thickness was not taken into account in computing, and was compensated for afterwards by rule of thumb, we must expect the actual focus to be shorter, probably by some inches.

We can also test for performance, if we have a cell ready in which to mount the lens. If not, we must wait till this is made. This is a job for the lathe and the brass-finisher, but the amateur who is capable of constructing his own object-glass will certainly not be beaten by the cell.

But when assembled and mounted we must not expect the lens to be ready for use in the telescope. In fact, the hardest part of the job is still before us. The set of curves chosen was, to be sure, one of those computed to correct spherical aberration. But it is a thousand to one that it does not. And for a very simple reason. The tables laboriously computed to remove spherical aberration all assume that the curves are truly spherical. This, as a matter of fact, they never are, except by accident. We can figure concave surfaces to any curve our skill is equal to. But of the figure of our two convex surfaces we know nothing at all. It may be anything, ellipse, sphere, parabola, or hyperbola, or a mixture of all four. All we can do is to try the lens and figure one or more of its surfaces according to what we see. And, fortunately, it is possible to correct the errors of the surfaces we cannot test by figuring one of the surfaces which we can test.

If there is an error in the convex lens which we cannot remove it is possible to compensate it. For example, if the center of the convex lens is too flat, making the focal length of the corresponding part of the object-glass too long, we can compensate this by making an equal area of the center of the concave lens also too flat. Or, if the whole lens, though regular in correction, proves under-corrected for spherical aberration (*i.e.,* the focal length becomes greater as we pass from margin to center) we can compensate it by figuring the back of the flint lens to a more or less pronounced oblate spheroid. If, on the other hand, the whole lens is over-corrected, we figure the back curve to a hyperboloid. The under-corrected condition is far more likely to occur, and it is for this reason that it is well to leave the preliminary figure of the fourth surface a sphere or an oblate spheroid. It is very easy to convert it into a hyperbola if necessary.

If the errors found on trying the lens are of large amount it may be necessary to figure all four surfaces to eliminate them. But if we can ascertain that an observed error is due to some one surface, it will of course be best to refigure the offending surface itself. How, then, can the offender be located? This is where the advantage of having as few convex surfaces as possible comes in. When we have two concave surfaces, we can ascertain by direct

inspection with Foucault's lamp and knife-edge if either of these is at fault. If not, then the fault must be in one or other of the convexes. To ascertain which of them is at fault is easy with the set of curves we have been working—viz., one having the second and third surfaces in contact. If a transparent liquid having nearly the same refractive index as glass be placed between these surfaces, they are optically abolished, and the lens behaves as if it were a solid one having only two surfaces. Therefore, if the defect be in the second surface it vanishes. If it still is there, it can only be in the first surface. Thus the offending surface is tracked down and its errors can be corrected *in situ.* Liquids suitable for the purpose are Canada balsam, castor oil, and glycerine.

Now as to the testing of our objectives. Till quite recently the only way of testing an objective was by actually trying it on a star. Many an optician cast longing looks on the ease and simplicity of Foucault's shadow test, by which mirrors can be figured so accurately, and longed for something equally simple for guiding his hand while figuring the surfaces of an object-glass. The writer believes he was the first to devise, and he certainly was the first to publish, a simple means to this desirable end. Let us recall the principle of Foucault's apparatus, referring to Chapters II and III.

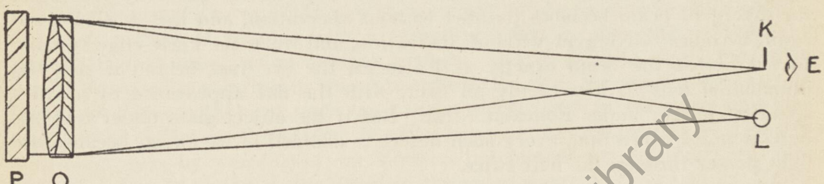

FIGURE 10

It is clear that we can test an objective as there described only by putting the lamp at one side of it and the knife-edge at the other. Also the distance of each from the lens must be twice its focal length. So, whereas a mirror requires a straight line of twice its solar focal length for testing it in, an object-glass will require four times its focal length. A 4-inch would therefore require 20 feet, a 5-inch 25 feet, etc. And, moreover, when so tested, the results would be unsatisfactory. For an objective is corrected for parallel rays, and the rays from a point two focal lengths distant are far from parallel In the case of a mirror this objection is got over by the simple little formula $A = \frac{r^2}{R}$, as explained in the chapter on zonal testing. But in an object-glass there is no R, or, rather, there are four R's, all different, and none of them having any relation to the focal length of the double lens.

The idea occurred to Professor Fullan, of the Alabama Polytechnic Institute, U.S.A., that the testing of a mirror could be simplified by placing the Foucault lamp at the solar focus of the mirror instead of at center of curvature, so that the returning beam would be parallel, receiving this parallel beam on a plane mirror which returns it to the concave, from which it is again

returned convergent to the eye and the knife-edge. In this way the necessity for using the $A = \frac{r^2}{R}$ formula disappears and the surface of a truly parabolic mirror presents the easily identified flat appearance which in Foucault's method characterizes the sphere. But the arrangements needed are awkward and complicated, and the method is not likely to supersede Foucault's. But in examining Professor Fullan's apparatus it flashed across my mind that this was just what was wanted as a workshop method for testing object-glasses. It did not take many minutes to set up the apparatus. A plane mirror in front of the object-glass, as close to the first surface as possible, Foucault's lamp and knife-edge at the solar focus of the lens, and the outfit is complete, as in Figure 10.

The light from the pin-hole lamp, L, at the solar focus of the lens, O, falls on the lens, and, after passing through it, issues as a parallel beam. As a parallel beam it falls normally on the plane mirror, P. It returns from the mirror still parallel, re-enters the object-glass parallel, as a beam from a star would, and is by it converged back again to the solar focus, where it forms an image of the pin-hole. As before in the mirror test, a slight *ecart* of the lamp to the left diverts the image to the right sufficiently to enable an eyepiece, or the eye itself, to receive it. If the objective is perfectly corrected, the divergent beam becomes parallel without aberration, and the parallel beam again becomes convergent without aberration, and when the knife-edge is made to cut across the beam exactly at its focus, the eye just behind it sees the illuminated lens darken evenly all over, with the flat appearance of a truly spherical mirror under Foucault's test. But if the object-glass under test has defects in its correction, every such defect is doubled in its effect, because the light passes through the lens twice.

The chromatic correction, as well as the spherical, is tested by this useful device, by examining the image with an eyepiece. On pushing the eyepiece inside, or drawing it outside, focus, the colors of the secondary spectrum are seen, as when the image of a star is examined in the same way in the telescope. Only in the apparatus the secondary spectrum, like all other outstanding defects, is doubled. In optical apparatus the name of "collimating lens" is given to a lens whose office is to render a divergent beam parallel before it enters an objective. We have therefore given to this method of testing the name of the Autocollimation Test, because the objective under test acts as its own collimator.

Now let us suppose that our objective is under-corrected for spherical aberration, as it is almost certain to be; because, in the absence of any check on the figure of the convex surfaces, these surfaces get almost invariably too much polishing in the center, with the result that the curve is too flat there and the central focus too long. This will reveal itself in the auto-collimation test as a forward bulge or hump towards the observer. Whereas, if the lens be over-corrected, it will look hollow in the center, bulging away from the observer. If the under-correction is not great, it may be remedied by working the back of the flint lens to a similar hump, making it an oblate spheroid, in fact. If too great for this, we must find which surface is at fault and try to

remove the flat center by working with a tool with the center more or less cut away.

If there is any uncertainty whether a visible defect is due to a hill or a hollow, the point can be cleared up by a very neat method given by Sir Howard Grubb in a paper in *Nature.* Rub the bare hand over the glass at the spot affected. The warmth communicated by the hand to the glass causes a slight bulge thereon. Now test again before it has time to cool. If the defect was due to a hill, it will be aggravated; if to a hollow, it will temporarily disappear, and you can watch it come back again as the glass cools. A hollow must be treated by polishing with a tool which acts on the rest of the surface and leaves the hollow spot alone. The remedy for a hill is obvious.

Far more difficult to treat than hills and hollows is a turned-down edge, a defect which nearly all object-glasses by second-rate makers suffer from. It is indeed the *bete noire* of the optician, always ready to show its objectionable presence on every surface polished with pitch. It is on account of the ever-present fear of turned edge that it is always advisable to keep pitch too hard rather than too soft. And one of the advantages of a slight admixture of beeswax in polishing pitch is that it greatly reduces its tendency to turn an edge. It is much easier to prevent turned edge than to cure it. Therefore, in polishing our surfaces we took care to use pitch on the hard side, and to finish our back surface if possible with a turned-up edge, as this will neutralize a possible turned-down one on another surface. But if, in spite of all, we find a turned down edge showing in the auto-collimation test, we must polish at our convex surfaces with hard tools, and tools slightly less in diameter than the lens, till the defect is eliminated. It often happens that we get rid of it partly with much ease by working at one surface, but cannot get any further. The best plan then is to attack the other in the same way.

The operator who has the skill to figure a mirror successfully will have no real difficulty in overcoming the very analogous problems presented by an object-glass, especially as his task is rather simplified than complicated by the four surfaces, since he can, to a considerable extent, play off one against another. Another point in his favor is that the so often troublesome edge is cut off by the cell, so that he is not bound to be so particular that his curves should be exact up to the extreme edge. It may also be mentioned that the circle by which the light leaves the object-glass is necessarily smaller than that by which it enters it; therefore, the cell flange may be a little deeper at the back than at the front without cutting down the clear aperture. A narrow defective zone on the back surface will thus be kept out of action altogether.

It will be seen also from the foregoing that, so far as the practical optician is concerned, the careful computing of curves to cure spherical aberration is waste of time. It is not too much to say that the operator who is skilled in figuring might safely undertake to produce a perfect object-glass with any set of curves whatever, provided chromatic aberration was corrected; trusting to figuring alone to correct the spherical aberration. The writer has seen a 3-inch object-glass whose curves, if spherical, would only define with the convex lens in front, so manipulated that it would define perfectly with

the flint lens leading, and not in its normal position. To such a length has skill in figuring been carried, that some amateur mirror and lens makers can juggle with curves to an almost unlimited extent, producing at will any desired form of concave surface, from the most extreme oblate spheroid to the most extreme hyperboloid.

The detection of a turned edge when using the auto-collimator, is similar to the corresponding operation on a mirror, with one difference: When examining the image of the pin-hole with an eyepiece, it is the disk outside focus which shows a hairy edge in the case of an object-glass with a turned-down edge. With a mirror, it will be remembered, it was the disk inside focus which was affected. When testing an object-glass on a star in the telescope it will be the same; and one of the first things to be noted will be the out-of-focus image of a bright star, outside focus. If this is circular and fairly sharp in outline, and its edge is slightly green in color, a favorable judgment of the lens may be formed at once, as the commonest defect of an object-glass is not present. Inside focus the expanded disk should be similar to what it is outside, except that the margin should be slightly purple instead of green. If the lens is properly corrected for both spherical and chromatic aberration it will come sharply to focus exactly at the point where the purple disappears and the green appears, or *vice versa*. At this point the image in a good lens is very nearly colorless.

When, satisfied with our workshop tests, we come to try our objective on a star it will be necessary first to see that the lenses are an easy fit in the cell, and that the counter-cell is screwed home, but not tight. The lenses should rattle very slightly when shaken. Then the cell is screwed home into its object-end and a look taken at a bright star with a moderately high-power eyepiece, say, 1/4 or 1/3 inch. The first view will not be a good one, as the objective will be "out of square." The star will have a flare on one side. With the type of objective we have been making, to remedy this the side of the objective next the flare must be pushed in or the opposite side pushed out. Let the screws holding the object-end to the tube be loose enough to enable the end to move when moderate force is applied. Place a short piece of wood against the cell and tap it in the required direction with the wooden handle of a screw-driver or other convenient object. If the cell has pull-and-push screws, so much the better.

When the image is as symmetrical as possible, put on the highest eyepiece you have, and focus carefully, and note the appearance of the star-image. It should be a tiny, circular dot, surrounded by one or two very fine rings of light. If these rings are too numerous, or are thick and coarse, spherical aberration is not fully corrected. If they are thicker on one side of the image than the other the squaring is still defective, and the side of the objective next the thick part must be pushed in a little more.

A slight movement of astigmatism is very often found in an objective when first tested, after all adjustments have been made as perfectly as possible. This shows itself by the image, a little out of focus, being not circular, but slightly oval, the major axis of the oval being one way inside focus, and at

right angles to that outside focus. The cause of this is slight flexure, probably present in both lenses. To remedy this the lenses must be rotated on each other a little at a time until a position is found in which the defect vanishes or is reduced to the smallest possible amount. When this is found, the edges of the lenses must be marked so that they can always be placed with certainty in their right relative position.

Some makers notch the edges and solder a pin into the cell to fit the notch, so that if removed for any purpose the lenses cannot be replaced except in the right way. Rarely indeed is a lens so perfect as to be quite indifferent to the positions of the components with respect to each other. If the oval images cannot be made to become circular in any position, one or other lens is seriously flexured, and it may be necessary to re-grind it. But this should not happen if proper care was taken in supporting the lenses correctly in the original working.

If badly astigmatic, the image at focus will be a cross instead of a small disk or a point. For this the only remedy is to return to the last stages of fine-grinding, and use greater care.

CHAPTER XII.

Mounting the Lens

The worker who has successfully finished an object-glass or mirror will, before he can use it, be obliged to provide it with a mount or "cell". An object-glass cannot even be tested accurately until fitted into its cell. It is therefore desirable to make this as soon as the preliminary polishing of the four surfaces is completed, before beginning the delicate work of figuring.

The making of an object-glass cell will be a nice little exercise in brass-fitting, just the sort of job that the amateur lathe-man enjoys. We require first of all a suitable set of castings, unless the lens to be mounted is quite small, not over $2\frac{1}{4}$-inch aperture, in which case a piece cut from a heavy brass tube of the requisite size may be used, and will save the trouble of machining a rough casting. But for a lens of any size castings are indispensable. If any quantity of brass scrap of fair quality is lying about, and a friendly founder can be got to melt it down, it will save expense.

We will require at least two castings, perhaps three. One of these will be for the body of the cell, a second for the counter-cell or screw-ring which confines the lens in the cell, and the third for the "end", the piece which fits

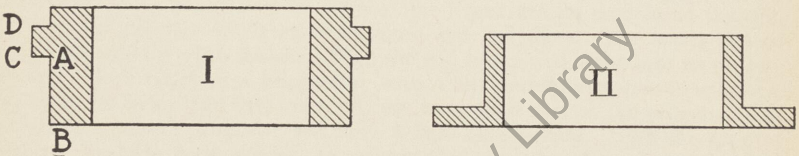

FIGURE 11

I is a cross-section of pattern of cell casting. If the portion A B *be made deep enough, a ring turned off the lower part can be used for the counter-cell, saving a separate casting and pattern. II is a form of casting for an adjustable cell. Two castings from the same pattern will serve—one for the cell, the other for the "end."*

on to the telescope-tube and into which the cell screws. It is preferable, however, to make the pattern deep enough to enable us to turn off a ring from the bottom of the castings after the preliminary machining, and to use this for the counter-cell, saving the making of a very thin and flimsy pattern which would be liable to break or warp in the moulding. Figure 11, I, shows the form of pattern required for the cell. By making the portion AB a little deeper than shown there will be enough metal in the casting to admit of turning off the lower portion and using it for the counter-cell. A similar pattern, but lighter, and without the flange CD, will serve for the "end".

A good lathe is, of course, requisite for dealing with the job, and the better the lathe the easier it will be to turn out a satisfactory article. But an ordinary plain lathe with 3-inch to 4-inch centers can be made to serve if the worker is ingenious; and if he can use "chasers" nothing else is required. The writer's tool is a plain 4-inch lathe provided with the usual

chucks and face-plate, but with an extra in the shape of a fine 5-inch 3-jaw scroll chuck, which is most extremely useful. To adapt this machine for screw-cutting the following additions were made to it: Firstly, on the driving-shaft a 2-step pulley of hard wood having one step double the diameter of the other, one 3-inch, the other 6-inch diameter, to bottom of groove, is fitted. This slides freely along the shaft, and can be clamped to it at any point by a set-screw. Secondly, behind, and rigidly attached to, the hand-wheel which operates the back-center screw is another wooden pulley $2\frac{1}{2}$ inches diameter to the bottom of groove. A couple of thin gut driving belts, crossed where they pass between the bars of the lathe-bed, connect the shaft-pulley with that on the hand-wheel when required, and can be attached or detached in a moment. In this way the hand-wheel can be driven at the rate of 6 turns to 5 of shaft, or 12 turns to 5. Now the lowest gear of mandrel to shaft is 4 to 1; so the speed of the hand-wheel to mandrel is 6 turns to 20, or 12 to 20—i.e., $3\frac{1}{2}$ to 1, or $1\frac{2}{3}$ to 1. But the pitch of hand-wheel screw is 9 threads per inch, so the mandrel makes 30 turns, or 15 per inch traverse of the poppet, according to which step is engaged. The next speed on mandrel pulley is $5\frac{1}{3}$ to 1, which gives for 15 and 30, 20 and 40 respectively, so that we have 15, 20, 30 and 40 threads per inch which can be cut. These are sufficient for most things in telescope work.

When a screw is to be cut the back center is removed and into its socket is placed a fitting which projects forward across the T rest and engages the chaser when held in position for cutting, driving it at the above speeds. The lathe is run alternately backwards and forwards a few times till the chaser has cut deep enough to guide itself. The belt of the screw-cutting gear is then cast off and the screw finished by hand. The expert Birmingham brass-fitter will no doubt laugh at this contraption; but it works beautifully, and there are no drunk threads after it.

Our first care after removing the rough exterior of the casting (an operation for which it is well to have a set of rough tools made of old files) will be to turn up the interior truly cylindrical and a nice easy fit for the object-glass. A slide-rest is the proper thing for this sort of job, but it can be done with care by means of hand tools, making plentiful use of the calipers. The flange against which the crown lens beds should be left wider than will be required, to be turned down afterwards. The outside is turned down next, leaving a flange at the point to which the cover-cap will reach when fitted.

Next the counter-cell may be turned up, leaving it just too large to enter. As this is a thin piece, it will be necessary to make a wooden chuck to hold it, and prevent distortion. A thick wooden ring, over which the brass ring fits loosely, will do. Split it at one side, put the brass ring on, slip the whole thing over the jaws of the scroll chuck, and expand the latter till tight. We can now turn up or screw the thin ring without fear of distorting it. A thread of 30 per inch is suitable for the counter-cell, and it should be an easy fit till very nearly home. The external thread by which the cell screws into the "end" should be a good deal coarser, 15 or 20 per inch. The "end" need not be anything but a plain cylinder, except for the internal thread at one end. The other end should be a fairly easy fit over the main telescope tube,

and while in position thereon should be drilled at three equidistant points, and screws fitted, each with a nut inside the tube. The holes in the tube should be broached out to a loose fit, or else a little longer than they are wide, to admit of a small amount of adjustment for squaring the object-glass (see Figure 12).

This is the usual plan in small telescopes. But it will save a lot of worry

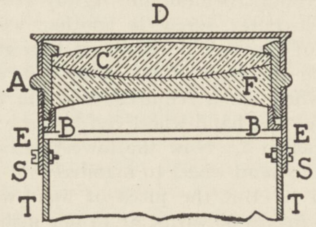

FIGURE 12

The usual form of cell for a small object-glass. A *is the cell;* BB *the counter-cell;* C *the crown lens;* F *the flint lens;* EE *the end;* TT *the telescope tube, and* SS *the screws for attaching the end to the tube;* D *is the cover-cap.*

afterwards if we have a cell provided with "pull-and-push" screws for squaring. A slight modification of the form of the castings for cell and end will be necessary for this (see Figure 11, II). And not only a modification, but a simplification. For the same pattern will serve for the castings for both cell and end, and if the cylindrical part be made deep enough to spare a ring

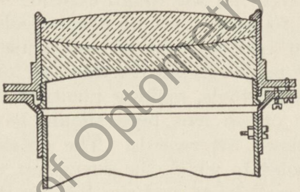

FIGURE 13

Push-and-pull screw cell. There are three equidistant pairs of screws, but one pair only is shown.

turned off for the counter-cell, one pattern of the form shown will do for the lot.

Figure 13 shows in section the form of the cell when completed. Great care is necessary in making the finishing cuts on the interior of the cell. It must be truly cylindrical, an easy fit for the lenses without pressure, and with just the merest suspicion of play between brass and glass. If overdone,

and too loose a fit, this may be remedied by inserting a strip of thin smooth paper as wide as the thickness of the object-glass between it and the cell. But this will not be necessary to a good workman. The counter-cell must not be screwed down tight, as strain of the glass will injure its performance very seriously. A slight rattle should always be heard when the cell is shaken.

The tube, which forms the body of the telescope, should be straight, strong and rigid. If these conditions be fulfilled, its actual material is of small importance, except for appearance. Brass is, of course, the proper material for a small refractor, and up to 3-inch diameter it will not be prohibitive in cost. But excellent tubes may be made of sheet iron, tinplate, wood, or even pasteboard. The suitability of the material will, of course, be partly determined by the size required. The writer on one occasion had an excellent tube made by a traveling tinker for a 3-inch object-glass. The man was so totally illiterate that feet and inches had no meaning to him. But being given a stick of the length of the required tube, and a strip of tin equal to its circumference, he made an excellent job.

The stops in the interior of a refractor tube may be turned out of wood. There are very often too many of these, and they are commonly made too small. One about half-way down the tube will be enough. It should fit tightly enough to stay where it is put, but not too tightly to be easily pushed up or down till the best position is found for it. It should not be only just large enough to pass the entire cone of rays from the object-glass; still less should it be so small as to cut down the aperture, as is too often the case. A good way of ascertaining whether the stops are too narrow is to put in a high-power eyepiece, point the wrong end of the telescope to the sky (or any bright object), and, looking through the object-glass, see if the tiny spot of light admitted by the eyepiece is visible from all parts of the object-glass, and right up to its edge. If not, the stops are cutting off some of the aperture, and should be removed, or shifted nearer the eye end.

To come to the eye end, the principal working part here is the rack-and-pinion focussing movement. This is a job which is hardly one for an amateur, and we would recommend purchasing it, as also the eyepieces, and for the same reason. They can be bought at a moderate price far better than the amateur brass-fitter could make them.

At least, three eyepieces should be obtained. If this number be decided on they should, for a refractor, be of about 2 inches, 3/4 inch and 1/4 inch, equivalent focus, respectively. If the telescope is of 4-inch aperture or more, four to six eyepieces will be found useful, and should range from 2 1/2 inches to 1/5 inch equivalent focus to enable the objective to do itself justice on all classes of objects.

Part III.

METHODS OF SILVERING GLASS

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Cleaning the Surface to be Silvered

This is the most important part of the process, whatever formula is used. The glass surface must be chemically clean. A greasy surface, which has not previously been silvered, should be cleaned with some such solvent as alcohol or ether. Following this, the surface should be scrupulously cleaned with nitric acid.

Make a swab by winding absorbent cotton on the end of a glass spatula or glass rod, with sufficient thickness of cotton so that there will be no danger of scratching the glass with the rod. With such a swab and pure nitric acid to which a little distilled water may be added, clean *every* part of the surface; considerable pressure should be used in rubbing with the swab. Do not let any part of the glass become dry in this process; if it does, swab and clean again.

Rinse off the nitric acid, for which ordinary water may be used at first, followed by distilled (or rain) water.

Finally leave the mirror in a tray or other container, covered with distilled water, until ready to silver. *No part of the mirror should be allowed to become dry.*

After cleaning with nitric acid, many advise a second cleaning with a strong solution of caustic potash, followed by an application of French chalk, and rinsing as above. The nitric acid alone will be found sufficient, provided the cleaning is thoroughly done, and plenty of pressure used in the swabbing.

In commercial silvering many manipulators follow the cleaning with nitric acid by a vigorous swabbing with a saturated solution of stannous chloride ($SnCl_2$), which is carefully rinsed off with warm water. This is regarded as an essential feature in most of the "secret processes" used in the trade.

Purity of Chemicals Used

All chemicals used in the formulae must be of high purity, of the grade known in the trade as C. P.; the use of impure re-agents will result in failure.

Distilled water is best; if this is not available use rain water. In some localities it will be found that the water from the taps will answer instead of distilled water. A test on a small mirror will decide this point. If the solution turns a light pink or blue when the silver nitrate is dissolved in the water, the water is probably too impure for the purpose.

Brashear's Process

This process is probably used more than any other for silvering the surface of large mirrors used in reflecting telescopes, and laboratory mirrors where a thick coat is desired.

For most work the following proportions will be found adequate:

$$\frac{\text{Square cms.,}}{40} \text{ or } \frac{\text{Square inches}}{6} = \left\{ \begin{array}{l} \text{No. of grams} \\ \text{silver nitrate} \\ \text{required} \end{array} \right.$$

For very thick coats, and for *astronomical* mirrors, many prefer a more liberal allowance of silver nitrate, about as follows:

$$\frac{\text{Square cms.,}}{27} \text{ or } \frac{\text{Square inches}}{4} = \left\{ \begin{array}{l} \text{No. of grams} \\ \text{silver nitrate} \\ \text{required} \end{array} \right.$$

Caution: In using the Brashear process keep the solutions, and do the silvering, at a temperature of about 15° C. or 59° Fahrenheit. In hot weather it is advisable to use ice to keep the temperature of the solutions below 18° C. (64° Fahrenheit). If warmer than this the resulting coat is apt to be soft, and there is danger of the formation of small amounts of silver fulminate, *which is very explosive.*

The Reducing Solution:

Rock candy	90 grams
Nitric acid (specific gravity 1.22)	4 cc.
Alcohol	175 cc.
Distilled water	1000 cc.

This reducing solution is preferably made up in advance; the older it is, the better it will work. If necessary to use it at once, the action may be improved by boiling it, adding the alcohol after it has cooled.

The Silvering Solutions: (Make up just before silvering)

A	Distilled water	300 cc.
	Silver nitrate	20 grams.
	Strongest ammonia, as may be needed	(see below)
B	Distilled water	100 cc.
	Caustic potash	10 grams.
C	Distilled water	30 cc.
	Silver nitrate	2 grams.

In solution A, after the nitrate is all dissolved, add ammonia gradually. The solution will at once turn a dark brown. Continue adding ammonia, drop by drop toward the close of the process, until the solution just clears up; avoid an excess of ammonia. Then pour in solution B; the mixture will again turn dark brown or black. Again add ammonia, drop by drop toward the close, and stirring constantly, until the solution just clears up again. It should now be a light brown or straw color, but transparent.

Next add slowly, stirring constantly, as much of the reserve silver solu-

tion, C, as the mixture will take up without turning too dark; it is important that the nitrate of silver be in excess. Continue this till there is quite a little suspended matter, which the solution refuses to take up. Filter through absorbent cotton.

When ready to silver, pour into this mixture about 6 cc. of the reducing solution for each gram of silver nitrate used, and pour at once upon the mirror, which has been lying covered by about the same amount of water as is used in the solutions; this water need not be poured off.

The process will be finished in from three to eight minutes, depending on the temperature of the solutions, which should never exceed 18° C. (64° Fahrenheit). It is well to make preliminary tests in small beakers or drinking glasses to get the time necessary as the coat is apt to bleach if process is continued too long. Keep solution in motion so that the thick sediment which forms will not deposit on the silver coat. A *very* light swabbing with loose absorbent cotton, over *every* part of the mirror, will be found advantageous in large mirrors, as soon as the coat begins to form. Avoid exposing the surface to the air for more than a second or two at a time to observe progress.

Get the spent solution off quickly at the close of the process; rinse thoroughly, first with ordinary and then with distilled water; swab lightly with absorbent cotton while rinsing if there is much "bloom" on the surface.

Drying, Burnishing, Etc.

Stand mirror on edge to dry and remove water at edges with blotting-paper.

For front surface silvering, burnish, after mirror is perfectly dry, by making a pad of softest chamois skin wrapped around a wad of cotton. Rub a very little of best optical rouge into this pad, and go over entire surface in circular strokes. Dust mirror and pad occasionally during the burnishing to avoid scratches.

Burnishing is not necessary for back surface silvering, as in ordinary looking glasses. The silver coat may here be covered with one or two coats of shellac and later covered with paint or other protector.

Thickness of the Film

Nobili's rings may be used to determine the thickness of the film. Place a very minute crystal of iodine on the silver surface; obviate the effect of air drafts by placing over it a small beaker, which should not, however, fit the surface tightly. Count the rings which will form around the crystal in a few minutes. Then the thickness of film will be:

To first dark ring	0.000,018 mm.	
To second bright ring	0.000,037 mm.	thin
To third bright ring	0.000,074 mm.	
To fourth bright ring	0.000,110 mm.	thick
To fifth bright ring	0.000,147 mm.	
To sixth bright ring	0.000,184 mm.	very thick
To seventh bright ring	0.000,220 mm.	very thick

General Information and References

Rubber gloves will be found a convenience.

Nitrate of silver stains on the hands, if freshly made, can be removed by bathing the hands in hot hyposulphite of soda, or a dilute solution (cold) of potassium cyanide (very poisonous; should not be used if there are cuts or abrasions on the hands).

The merest trace of chlorine, free or in combination will cause failure. In silvering small mirrors, where small amounts of solution are used, use care that the solutions are not contaminated by the salt in the natural perspiration of the hands.

Brashear's Method, *Astrophysical Journal,* 1, 252, 1895.

Draper's Method, *Smithsonian Contrib.,* 1856, XIV.

Liebig, *Annalen der Physik,* 1867, Sup. V, 153.

Chattaway, *Chemical News,* Sept. 27 and Oct. 4, 1907.

Curtis, "Methods of Silvering Mirrors," *Publ. Astron. Society of the Pacific,* 23, 13, 1911.

"The Making of Reflecting Surfaces," published by the Optical Society.

[Editor's Note: The following list, expressed in the customary weights and measures, was calculated specifically for a 6-inch mirror, by Porter.

Reducing Solution: Loaf sugar, 3 oz.; nitric acid, of specific gravity, 1.22, 1/4 oz.; pure grain alcohol, 7 oz.; distilled water, 40 oz. (at druggist's).

Silvering solutions: Solution A—distilled water, 8 oz. (one glass); silver nitrate, 1/2 oz.; strongest ammonia, as may be needed (see text of Bureau of Standards Circular, quoted above). Solution B—distilled water, 4 oz. (1/2 glass); caustic potash, 1/4 oz. Solution C—use one-tenth of solution A, reserved for that purpose. In adding ammonia do not try to dissolve the black flakes.

The quantity of reducing solution given above is rather large, but it is quite inexpensive. Use 1 avoirdupois ounce of reducing solution for each 75 grains of silver nitrate used. One ounce avoirdupois contains 437 1/2 grains. One ounce apothecaries' weight contains 480 grains. If using the latter, allow one ounce of reducing solution for each 82 grains of silver nitrate. For silvering, use a glass dish or enamel ware pan an inch or two larger than mirror and three or four inches deep, so that solution may be kept in motion during silvering. Place mirror in dish, concave side up. The pan and back of disk will take some of the silver but the half ounce allows enough for six inch mirror in spite of this. When large flakes are seen in the spent solution the process is done. Disk may be lifted near surface to inspect. Don't touch its face. The Nobili's rings test destroys a ring of the silver. Through a good coat one can just make out the muntins of a window.

If a clean, unstained coat of silver, clear up to the edge of the disk, is to be guaranteed, rubber gloves are almost a necessity.]

The remainder of Part III consists of notes added in 1928, at time of publication of the second edition.

Silvering: No part of the work has occasioned so much difficulty as silvering. The instructions as given in the first edition were somewhat indefinite in places, for example, "too dark", and "quite a little" (p. 132) are delightfully elastic, but the first edition was made up in a hurry, to supply an unexpectedly sudden demand. Many beginners advised The Editor that they therefore learned to silver only after persistent effort.

On the other hand, no man living can guarantee to produce uniform, sure-fire results in silvering, and this fact, namely, that they all—professionals included— fall down some of the time, may give renewed courage to some who may have been tempted to give up after two or three failures.

Quite often, also, the old hand can give no reason for his failures. Like the family baby, a job of silvering usually acts up at its worst when you are bent on showing some expectant visitor or guest just how it is managed. Again, if you get a fine coat on your first job it is unwise to become too confident; it may be beginner's luck. However, it is possible, with care, cleanliness and system, to get good results two-thirds of the time. *Cleanliness:* be fussy about it, for here it pays well.

First, regarding the Brashear process described on page 131, many have asked why we seem so partial to that particular method. Why slight the others? The Brashear process was chosen because it is believed to give the best coats. According to James Wier French, D.Sc., of Glasgow, the Brashear process surface reflects about 6 per cent more light than the Rochelle salt surface, and about 8 per cent more than by the tartaric acid process. The formaline or formaldehyde process, while simple and rapid, is rarely used, and it gives a darker surface than the Brashear or Rochelle processes. Finally, there must be some good reason why nearly all of the big mirrors are regularly silvered by the Brashear process. However, the free Letter-Circular 32 of the Bureau of Standards, Washington, D. C., describes all of the methods, for those who wish to try the others.

Regarding the "pure grain alcohol" stipulated on page 133 and in virtually all silvering directions: it would almost seem that parts of the United States had adopted prohibition, as numerous amateurs seem to have had difficulty in obtaining this kickful commodity. When this strange fact became known the question arose: "Why has grain alcohol always been stipulated, anyway?" The only valid answer seems to have been that ancient tradition demanded it. Those recently concerned with telescope making having no respect for tradition, other kinds of alcohol were accordingly tried, and lo and behold, they worked.

First came a note from the Reverend Harold N. Cutler, who wrote as follows:

"From experiments which I have made it seems possible to substitute wood alcohol for pure grain alcohol for silvering mirrors by the Brashear process. First it is necessary to test the alcohol for bichloride by boiling up some silver nitrate in a small quantity of the alcohol. The solutions are mixed in the usual

way, making the above substitution in the reducing solution. If this is freshly made up its action is quickened by boiling. The process of silvering will be somewhat slower than when using pure grain alcohol, lasting about 20 minutes for an adequate coat and being complete when black 'gun powder-like' grains begin to deposit in the mirror. For some reason I found that the reduction of the silver did not take place rapidly until I had added a few drops of concentrated nitric acid and a stick of caustic potash dissolved in water, to the mixed solutions. Upon adding these the solution changed from colorless through brown to black as normally, and the silver deposited on the test glass evenly and rapidly."

Stephen F. Darling, an amateur worker who is also a chemist, in referring to the use of denatured grain (not wood) alcohol, states:

"I do not think it advisable to use every kind of denatured alcohol for silvering mirrors, for two reasons. First: alcohol is denatured in many ways for different purposes and many of these denaturants are detrimental to the silvering solutions. Second: much of the denatured alcohol sold is for crude purposes such as for automobile radiators and is of a low grade of purity, and purity is one of the important factors governing a good coating. The denatured alcohol you used probably contained tartar emetic, because of the white precipitate which came down when you added nitric acid. This substance is added in many medicinal alcohols for external use."

Just about this time The Editor happened to visit the optical shop at the U. S. Bureau of Standards, Washington, D. C., and discovered through Hugh G. Boutell of the Bureau, himself an amateur telescope maker, that the silvering there is now done with common "Alcorub", using the Brashear process. Now anyone can get "Alcorub" at any drug store, anywhere, any time. So that seems to settle it. "Alcorub" is denatured grain alcohol, evidently having none of the objectionable qualities mentioned above by Mr. Darling, who adds to the list of candidates another rubbing alcohol called "Rubcohol", and says there are still others of a like nature.

The last word on silvering is contained in *Popular Astronomy,* June-July and August-September issues of 1911, by Dr. Heber D. Curtis, Director of Allegheny Observatory. The article, entitled "Method of Silvering Mirrors," runs to 20 pages.

The amateur would do well to obtain "A Discussion on the Making of Reflecting Surfaces," published by The Optical Society. (See directory.) This is a 44-page book containing 13 papers delivered in 1920, before the Physical Society of London and the Optical Society. They include a history of silvering; a most complete bibliography; workshop notes on silvering; a paper by Prof. Ellerman and Dr. Babcock of Mt. Wilson Observatory, telling how they silver the great mirrors, and one by Dr. C. R. Davidson, telling how the mirrors are silvered at the Royal Observatory of Greenwich. Also, more advanced matter on the deposition of "half-coated" mirrors of various metals by cathodic sputtering; platinizing glass mirrors by the burning-in process, etc. In this publication Dr. French states that the principal cause of tarnished mirrors is minute particles of saliva! (If one will place a person in a strong sunbeam shining into a dark room and get him to talk, the discovery is likely to be

made that we all "spray" or atomize, more or less, when we talk.) His method of spreading lacquer (see page 15) is to place the mirror on a rotating table and drop the lacquer in the center, from which it spreads by centrifugal force. F. J. Hargreaves of England rotates the mirror on a vertical spindle, at three revolutions per second for a 6½-inch, and for other sizes at speeds inversely proportional to diameter. Rotation is continued until dry, and a few minutes extra. Color bands may be noted during rotation, but these should give way to uniform color as the lacquer spreads. Rotate until rim of lacquer at edge is dry; or take it up with a blotter, else it may run back.

To digress at this point: The directions for the use of lacquer, as stated on page 15, have not always been closely followed. In particular, a number of silver coats have been ruined by attempting to paint on the lacquer. Moreover, the manufacturers, accustomed to recommend a dilution of 2 to 1 for protecting ordinary silverware, etc., do not in every case furnish the requested 6 to 1 dilution (8 to 1 would be even better). The 2 to 1 dilution spoils the coating and necessitates resilvering. To determine which dilution has been furnished the following may suffice: Lacquer diluted at 2 to 1 is almost as thick as olive oil. It flows in an almost unbroken stream from the end of a small stick, and when poured over a piece of glass it runs down quite deliberately. Lacquer diluted 6 or 8 to 1 is nearly as thin as water, it drops from a stick in separate drops and quickly runs down a pane of glass. If received in 2 to 1 dilution a little amyl acetate may be obtained from the drug store and the proper dilution made.

Several amateurs have expressed fear that lacquer will injure the optical qualities of their mirrors. This method of protecting them is not, however, a novelty. Bell's *The Telescope* contains a recommendation of lacquer which has been used on the 24-inch reflector at Harvard for years. Porter has used it on many mirrors. In applying the lacquer it is simply poured on, the mirror being held in the hand and tilted in various directions until the whole surface is wet. Then it is poured off and the mirror stood up to dry, and *without being touched.* The job takes less than a minute. *Do not use a brush.*

When the lacquer is properly applied, and dry, the surface will be crossed by one or perhaps two bands of inconspicuous color, blue at the top edge, then green, then pink at the bottom. These are interference fringes caused by the interference of rays reflected respectively from the upper and under surfaces of the lacquer, and they furnish an accurate measure of the thickness of the coat of lacquer. This coat is in the form of a wedge, naturally thickest at bottom where the lacquer tends to settle, as it dries. If there is only one blue-to-pink series of colors (one fringe) it shows that the butt or bottom edge of the wedge is not more than 1/100,000 inch thicker than the top, and will therefore not affect the reflected light, whose wavelength averages 1/50,000 inch. (The theory of these fringes where monochromatic light is used, as directed on page 52, is explained in the Government publication listed on page 231; where mixed light—daylight, for example—is involved, the colors produced are not the exact colors of the spectrum, but are shades whose cause is beautifully and simply explained under "Newton's Rings" in Thompson's *Light, Visible and Invisible.*

An alternative to lacquering the silvered surface is the use of a pad of absorbent cotton kept against it when it is not in actual use. This keeps the air away from it and will prevent serious tarnishing for quite a long time, though it leaves lint on the glass. Cut out a thick cardboard disk about the size of the mirror and loosely sew to it a pad of absorbent cotton, taking pains that the cotton makes fair contact with the mirror clear out to the edge. There is no need to press this fluffy pad tightly against the mirror; its own weight will suffice.

John C. Lee keeps his mirror out of doors in a common earthenware crock in whose bottom some calcium chloride is kept. This chemical, which can be got at the drug store, has a perpetual thirst—until completely satisfied, and thus it keeps the atmosphere dry inside the crock, whose cover should first be ground to a fairly airtight joint by means of carbo. It is well to keep the mirror out of doors so that it will always assume out-of-door temperatures. A mirror kept in the warm house and brought out for use will perform relatively poorly for a half hour or so, while it is changing temperature.

Porter inverts a mirror on a piece of plate glass, sealing it airtight without further ado. Others keep camphor near it. If it is lacquered these methods of protection are unnecessary. Returning to the silvering process, John C. Lee makes the following observations:

"On experimenting with the Brashear process it was noted that the silver as it deposits on the glass is at first very brilliant but, as the film grows thicker and particles of precipitated silver begin to cloud the solution, the film also begins to cloud. If the film is allowed to develop to a thick coating the mirror is apt to be hard to polish and unsatisfactory. To avoid the ill effects of the heavier precipitates a plan of conducting the silvering process in a series of fresh baths was tried with considerable success. The resulting mirror had a brilliant, thick, opaque film of silver that required very little polishing. A 6-inch mirror was arranged with a rubber collar about it to form a tray, and the solutions were mixed on a basis of a total of 10 grams of nitrate of silver. After the A, B and C solutions were properly brought together and filtered, the resulting silver solution was divided into three equal parts. The proper amount of reducing solution for 10 grams of silver nitrate was also divided into three parts. Ingredients for three separate plating baths were then ready for mixing as required. Three minutes were allowed for the deposit of silver from each bath and the mirror was carefully washed with distilled water between the baths." At Mt. Wilson the silvering solutions are similarly divided, although into two instead of three batches.

How thick should the coat be? Some say thick enough so that when looking out of a window through the mirror one can barely see strongly illuminated objects. Others specify a coat through which the Sun itself cannot be seen. As Curtis says, "a thick coat is better in every way." Ellison has said, "The right sort of a film is as opaque as a half-a-crown. If you can see the Sun through your film, it is not thick enough."

Most local druggists carry a small stock of silver nitrate, but this is likely to be old and inferior (not chemically pure). The way to make sure is to make him get you some that is chemically pure. It comes in neat little one-

ounce bottles and is in crystal form. On a pinch one can order it one's self—one place is Charles Cooper and Co.

When the mirror is cleaned with acid for silvering, rinse it and watch to see whether it dries evenly or in spots; if the latter, it is not yet clean.

In clearing up with ammonia the second clear-up usually takes about half as much ammonia as the first. The second is the critical one. The second solution never comes out as clear as the first; some blobs are left.

When burnishing, bear on just as lightly as is humanly possible on the first time over. Scrub off the pad on a knife now and then.

A hint to the wise is contained in directions for silvering mirrors published in *Popular Astronomy,* Volume 30, page 93, by the late Everett T. King of Harvard College Observatory: the mirror is kept about 10 or 20 degrees warmer than the solution. We have heard the same thing from numerous sources. This is not definitely required; perhaps it raises the percentage of successes. If anyone tries it his results would interest The Editor.

Finally, when we silver a surface, what actually takes place? Stephen F. Darling, at The Editor's request, has kindly summarized the chemistry of silvering in the following note, prepared especially for this occasion: "The chemical reactions involved in the process of silvering can be compared to those which occur in the smelting of an ore to obtain the pure metal. Here the pure silver ore is the silver nitrate uncontaminated with other metals and the smelting agent is the reducing solution. To the chemist, the process is perfectly rational and can be carried out by him in the laboratory with ease. To the layman, the process seems secret, but it can be carried out with equal ease after a little practice.

"The reaction consists in the slow deposition of metallic silver from a solution of its salt by means of a chemical known as a reducing agent, the reaction being called reduction by chemists. Among the many reducing agents available are formaldehyde, Rochelle salts, dextrose and fructose. Our reducing agent is cane sugar, which in the presence of a small amount of nitric acid is converted into dextrose and fructose, the last two reducing agents above mentioned. This conversion of cane sugar into its two components is a slow reaction, so the reducing solution improves with age and must stand for at least one week before using. The alcohol is added to the solution for purely empirical reasons and is not absolutely essential to the process. There are two reasons why cane sugar (beet sugar will serve as well) is chosen for our particular purpose. First, it is a weak reducing agent in a sense that the silver is deposited slowly and uniformly; and secondly, it is one of the commonest, yet one of the purest substances easily obtained.

"If a solution of silver nitrate were treated with the reducing solution without first adding ammonia and potassium hydroxide, the silver would be instantaneously thrown out of solution as a black mass. For our purpose the silver must be deposited slowly and in the finest state of division, so that the particles or atoms of silver have sufficient time to arrange themselves in the positions they occupy in bright, solid, metallic silver. This slow formation is accomplished by the addition of aqueous ammonia to the silver nitrate, which first

throws down silver oxide. This precipitate in turn is redissolved to form again a clear solution of a complex silver ammono nitrate. Even this type of solution can be reduced to silver, but heat is required to accelerate the reaction, so this method is not suitable for the silvering of telescope mirrors.

"Potassium hydroxide in the calculated amount is next added, again causing the black silver oxide to precipitate, and it is brought into solution once more by the addition of more ammonia. Since at this state even the most careful technicians usually have a slight excess of ammonia present, a little silver nitrate solution is now added to give a slight excess of silver. The amount necessary in this last step should cause a distinctly perceptible black precipitate, which is usually filtered off.

"Such a solution now contains the original silver nitrate in a form which will give up its silver at the right speed under the influence of the reducing solution at a certain temperature. A rise in temperature from that which is specified will cause the silver to precipitate more rapidly until a point is reached where the silver would deposit in a spongy mass varying in color from gray to black, depending on the conditions of temperatures and concentration.

"One can see from this brief explanation that the alcohol does not play any part in the reaction itself. It is added empirically, and its effect must be purely physical, enhancing the quality of the silver coat for some unknown reason.

"In conclusion, it would be well to emphasize some points which are most important for success. The directions should be followed with utmost care, especially in regard to the purity of chemicals, temperature, cleanliness and amounts of material. No guesswork will succeed, since the amounts of material have been carefully proportioned. Pure dextrose, now available from most pharmacists, has been used with success in place of the cane sugar and nitric acid, and has the advantage that the reducing solution can be used immediately.

"Lastly, under no circumstances save any unused silvering solution or keep it longer than one day after it has been prepared, since it develops a small sediment of an extremely explosive compound. Several serious accidents are on record resulting from ignorance of this last precaution."

The Editor believes the amateur fraternity will wish to give Darling a vote of thanks for this interesting exposition of the why of the silvering process. So far as is known it is the only similar statement that has ever been published.

Part IV.

CHAPTER I.

Telescope Oculars

By CHARLES S. HASTINGS, Ph.D.
Emeritus Professor of Physics at Yale University.

The easiest way to acquire a practical knowledge of oculars, their merits and defects, is to make a few properly directed experiments, such as those described below.

Assume for the moment that we have a good telescope, either refracting or reflecting, of which the focal length is fifteen times the aperture, which is the ordinary ratio for large astronomical telescopes; take a simple plano-convex lens of about three-fourths of an inch focal length and make the following observations:

EXPERIMENT I

With the flat side toward the eye it will be seen at once that the extent of the field will depend upon the position of the eye and that at one particular point the field is at its greatest, growing smaller either when the eye advances or recedes. Turning the telescope toward a bright field it will be found that there is, just where the eye should be placed for largest field, a bright circle which is in effect the image of the objective. This we shall call the *ocular circle.* The diameter of the objective, divided by the diameter of this circle, is exactly equal to the magnification of the telescope. As it is easy to measure these diameters, even with no more than a pocket rule and magnifier, within two or three per cent, it enables us to determine the magnification with all necessary precision. But this observation carries us farther toward our goal, for it enables one to eliminate all reference to the focal length of the telescope; in short, if the optical circle is large we are dealing with a low power ocular, if small the ocular rates as a high power.

Observe some convenient object at a distance—a brick wall with well marked courses will serve admirably—and note the defects in the image. These defects may be cataloged because they will yield not only much information but also definitions applicable to all oculars.

(1) Strong prismatic colors will be seen, increasing in intensity as one recedes from the center of the field. If the object observed is light on a dark ground it will be found to be blue on the outer side and red on the inner; if dark on bright ground the order of colors is reversed. This error, perhaps the most objectionable one of all, means that the ocular magnifies blue more than red, and is therefore called *chromatic difference of magnification.*

(2) A line which appears straight when passing through the center of the field becomes curved when displaced from the center; always convex toward the center, the curvature rapidly increases toward edge of field. This error is called *distortion.*

(3) If the telescope is adjusted for best definition at the center of the field, it will be found that the ocular must be displaced inward in order to secure best vision for a region not at the center, in other words, the field is not flat. This error is called *curvature of the field*—not to be confused with (2).

(4) If the telescope be adjusted for a point at a distance from the center of the field it will be found necessary to alter the adjustment in order to secure best vision on a line at right angles through the same point. The brick wall furnishes an easy test of this point. The error is called *oblique astigmatism.*

(5) Observe an object like a thin twig, or a telegraph wire against a bright sky; if the ocular is pushed in, the object will appear orange; if withdrawn it appears blue. If the object is bright on a dark ground—such as a star, real or artificial—the colors will be reversed in order. The colors named must be distinguished from the green and complementary violet which belong to an ordinary achromatic object glass, though not to a reflector. The error is called *chromatic aberration.*.

(6) There is another error, much more difficult to detect, since, in the case of a single lens, it is small, and also because it depends upon the quality of the objective: that is the difference of appearance of a star image inside and outside proper focus. It is called *spherical aberration,* and is easily detected in the familiar Huyghenian ocular.

Experiment II

Reverse the ocular so that the convex side is toward the eye; then it will be found that all of the above errors are exaggerated except (5) and (6); the former remains unchanged and the latter is lessened.

We are now in a position to detect and explain the errors of more convenient and familiar oculars, since we have not only their names but also experimental knowledge of them. The most celebrated of these is the Huyghenian ocular, since, omitting those used with a micrometer, probably ninety-nine in a hundred employed in the past two centuries are of this type. It is often called a *negative* ocular—a very ill-chosen name because there is nothing negative about it. The term is supposed to convey the fact that one principal focus is between the lenses, which precludes its use with a filar micrometer.

Huyghens was one of the greatest philosophers of all times and his discoveries and inventions are almost innumerable; here, however we are concerned only with the invention named above. He discovered, doubtless by experiment only, as optical theory was not sufficiently advanced, that if the ocular is made of two lenses separated by a distance half as great as the sum of their focal lengths, the worst of all the faults of the ocular, that is, the chromatic difference of modification, would disappear. Moreover, he knew, just as the foregoing experiments have shown, that the shape of the lens has much to do with the aspect of the field. The final result of his invention was a two-lens ocular as shown in Figure 1, A, with the following prescription: Both lenses plano-convex with plane side toward the eye; the

one next to the eye is called the *eye-lens* and the other the *field-lens.* Focal length of eye-lens 0.5 inch; of field-lens 1.5 inch; separation 1.0 inch.

Such an ocular will yield the same magnification as a single lens of 1-inch focal length and will practically eliminate errors (1) and (2) while (3) and (4) and (5) are little changed; (6), however, is much increased, being 1.5 times as great as that of a lens such as used in Experiment II of like power. It should be emphasized that for low powers—when the ocular circle is more than one-tenth of an inch in diameter, for example—nothing better need be looked for. Moreover, the ocular is easily constructed by the amateur optician. Only when an exceptionally large field, as for a comet-seeker, have I found it advantageous to replace it.

High Power Oculars

Whenever the ocular circle is less than one-tenth of an inch in diameter the ocular in use may be properly styled a high power ocular. If the diameter is half this value we are approaching the limit of useful powers; indeed, with a diameter of about one-sixteenth of an inch the telescope, if

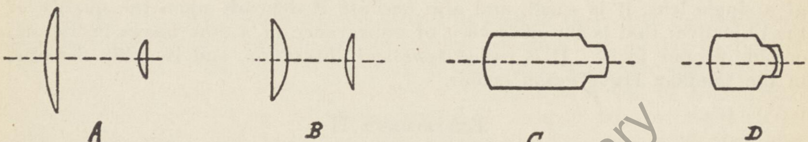


Figure 1

A represents a Huyghenian or "negative" ocular, B a Ramsden or "positive" ocular. C is a solid type and D a new solid ocular with a cemented flint glass cap or wafer. All four are described more fully in the next chapter.

quite perfect and if, at the same time, the eye of the observer is of normal acuity, the instrument is practically at its highest efficiency. By this is meant that in a well lighted landscape more fine detail can be seen with this magnification than with one greatly lower or higher.

The reason of this is interesting and instructive. With low powers, provided that the pupil of the eye is as great as the circle itself, the inherent defects of the eye, especially the radial structure of the lens and the spherical aberration, cease to be negligible. If the pupil is smaller than the ocular circle the observer is utilizing only a portion of the aperture; for example, if one is looking at the full Moon with an ocular which gives a diameter of one-fifth of an inch to this circle and the pupil has a diameter one-half as great, the effective aperture is reduced to one-half, and only one-fourth of the transmitted light reaches the retina.

The limitation in the other direction is also easily explained. If the ocular circle is too small, defects of definition due to the finite length of light waves become important. A simple experiment will yield a striking proof of this statement. With a fine needle make a small round hole, say one one-hundredth of an inch in diameter, in a piece of metal foil and observe a well lighted landscape through it; it will be found that much of the

finer detail—light twigs against the sky, for example—will vanish, although there is no lack of light. If one thus observes a distant light at night another peculiar phenomenon will be noticed—the light will appear as a disk surrounded by one or two bright rings. This gives at once the upper useful limit of magnification in a telescope. When a star, under favorable atmospheric conditions, appears as a distinct disk with one or two inconspicuous concentric rings the magnification approaches this limit. An ocular circle of one-thirtieth of an inch may be regarded as conformable to this standard, although higher powers are instructive and sometimes, with close and unequal double stars, they may prove useful.

There is one experiment that everyone interested in telescopes should try; that is to use a negative lens as an ocular. The eye-glass of an opera glass will serve. It will be found that the ocular circle is inside the telescope where the eye can not reach it and therefore the field is greatly restricted. This teaches us something of what Galileo and his contemporary astronomers had to contend with; and it also makes one regret that the discoverer of the satellites of Jupiter did not become acquainted with the first telescope of Lipershey, which was undoubtedly an inverting one, instead of his erecting type.

It is not necessary to extend this chapter by describing my efforts to improve the Huyghenian ocular and my ultimate preferences, since all of this is readily accessible.

There is one thing which may be added because it does not appear in the article cited, and which may stimulate some enthusiastic optician to try a similar experiment. I improved greatly the field in the "solid ocular" (C, Figure 1) by altering the eye-end by a cemented double-convex lens of highly refracting barium crown. This is illustrated in D, Figure 1. Constant and long continued use of this type warrants high commendation.

CHAPTER II.

*Astronomical Oculars**

By Charles S. Hastings

It is a curious and interesting fact that an ocular invented in the seventeenth century should survive in almost universal use until the present day. It was a very remarkable invention by Huyghens, to whom science owes so much both as astronomer and as physicist, and perfectly adapted to the long telescopes with single objectives of his time; how important the invention was one may easily discover by trying to direct a telescope unprovided with circles and finder and supplied with a simple lens for an eyepiece. Notwithstanding this the ocular is a very bad one for use with the modern achromatic objective. To demonstrate the truth of the statement I intend here to describe various oculars with an analysis of their several merits and defects. Moreover, I hope to give such complete details of their construction that amateur telescopists may be prompted to make them for themselves and add to the present limited experience of other types.

It is much to be deplored that there are so few amateur lens makers among Americans. There is a considerable and growing number of enthusiastic makers of mirrors for reflecting telescopes but they appear reluctant in making their own oculars. This is to be regretted because it is immeasurably easier to make a small lens than to make a mirror of significant size, and the making of small lenses is a very fascinating pursuit well within the powers of anyone possessing moderate mechanical aptitude and having command of an ordinary lathe. It is true that for the final grinding and polishing a vertical spindle has marked convenience, but such a tool is not indispensable and if desired it can be easily constructed from a so-called "polishing head" held in stock by most hardware dealers and costing a very little. My own apparatus is thus made and is driven by a small sewing machine motor. One disposed to follow an experiment of this kind must, however, provide for a great reduction in speed of revolution from motor to spindle.

A.† Huyghenian Ocular

This, the most universally used, has many merits. It admits of a large angular field of forty degrees and is very free from distortion, that is to say, a straight line in the field shifted from center to edge retains its appearance of straightness; moreover, the focal length is the same for all colors, hence objects do not assume prismatic colors when shifted from center to edge of the field. This last property may be best defined as freedom from chromatic difference of magnification.

The defects of this form are various. The field is so strongly curved, being

*Reprinted by permission, from *Popular Astronomy*, issue of June-July, 1926.

†The letters *A*, *B*, *C* and *D*, in the present chapter, refer to the same illustrations which accompany the previous chapter. For a further discussion of eyepieces the reader is referred to the special chapter in Bell's *The Telescope*.—Ed.

convex towards the eye, that only about twenty-five degrees of the field can be regarded as satisfactory; but its most serious defect is in its color error. Ordinarily regarded as achromatic, because it possesses the same focal length for all colors, it has a variation in the position of its focal planes one-half greater than that of a simple lens of the same power. In short, this ocular as described below has its blue image 0.03 inch nearer the eye-lens than that of the orange-red. To make this statement quantitatively accurate it may be paralleled by stating that a change of 0.01 in the index of refraction, which corresponds to this change of color, gives a spread of 0.03 of an inch for the effective color error at the axis. How serious a defect this is appears at once when it is recognized as about ten times the average error of focussing. It follows that a much higher power is required in the ocular for exhausting the definition of a properly corrected objective.

The fact that the first principal focus falls between the lenses is not important when regarded as part of a visual apparatus alone, but it precludes its use with a filar micrometer. This feature is embodied in the name—not very felicitously chosen—negative ocular. More important from our present standpoint is the loss of light reflected back towards the source so that only eighty-three one-hundredths is transmitted.

B. Ramsden Ocular

The necessity of having the first focal plane outside the system for micrometric work prompted Ramsden to the invention of his well known "positive" ocular. This in the hands of different opticians is of somewhat varied construction, but that defined below is a copy of one made by the famous English optician Dolland which has been in the possession of Yale University for nearly a century. Probably it cannot be improved upon.

The qualities of this ocular can be briefly stated. Its permissible field of forty degrees is large, but satisfactory vision is limited to about twenty-five degrees because of the marked chromatic difference of magnification. It is very free from distortion and the field is less curved than that of the Huyghenian; also the error which we have styled chromatic spread of the focal distance is reduced by one-half, a distinct improvement. On the whole this form must be rated superior to the preceding one, for axial vision at any rate, although having the same number of free surfaces it does not surpass it in transparency.

C. Solid Ocular

The origin of this form is quite unknown to me. It is true that it was patented about the middle of the last century by Tolles as an eyepiece for the microscope, a use which would be difficult to defend, but a lens maker who had been employed by both Tolles and his predecessor, Spencer, assured me that it was very much older than assumed. It was a description of this ocular by Mr. Stendicke, the lens maker alluded to, which led me while still a school boy to make many experiments with it. Later experience of many years has proved its appreciable superiority to more familiar types. Its defects are obvious. Its field is small—I have been accustomed to restrict the angular field, by a dia-

phragm in lower powers and by the containing cell in the higher, to a little more than thirty degrees, of which only the central twenty could be deemed thoroughly good. It is not free from distortion but the central field is essentially flat and there is no chromatic difference of magnification. The faults are more than compensated by absolute sharpness of definition and a transparency ten per cent greater than that of a two lens system. For many years I was entirely content with these oculars, of which I made a set having focal lengths of three-fourths, one-half, one-third, one-quarter and one-fifth of an inch. The highest power was of infrequent use of course, and any much lower power than that of the first in the series would fail to exhaust the definition of a thoroughly good objective and therefore fail to exhibit superiority to familiar types. At present I have discarded this form for that to be described immediately, except one of a half inch focal length into which, just where the shoulder appears in the illustrative sketch, I have replaced a portion of the crown glass by a properly chosen disk of dark, neutral tinted glass. This, with the customary Herschel reflecting wedge, makes an ideal system for the study of the surface of the sun, since the faults named above are of no consequence in this case. A copy of this is recommended with confidence.

D. A New Solid Ocular

Several years ago it occurred to me that it might be possible to make an ocular having all the excellences of those already described, provided that the simplification of a single variety of glass were abandoned. The success of the effort is unexpectedly great. This type, which is fully described below, is positive and can thus be used with a filar micrometer. It is not entirely without distortion but the exceptional flatness of the large angular field more than counterbalances this defect, a defect wholly unrecognizable in ordinary astronomical use.

The materials used in these oculars are an ordinary crown glass of a mean index of refraction of 1.5137 and an ordinary flint of mean index 1.6153, the latter only employed for the small cap at the eye end of the ocular. The relative dispersion of the two materials is 1.93. Such glasses are readily procured; moreover, it is obvious that a departure from these constants by a unit in the fourth decimal may be ignored as giving rise to less than the inevitable errors of even careful construction.

The radii and thicknesses (or separations) are given in the table.

Tables of Constants for Construction

	A	B	C	D
r_1	+1.085	∞	+0.675	+0.871
r_2	∞	—0.801	—0.421	—0.240
r_3	+0.381	+0.727		—0.509
r_4	∞	∞		
t_1	0.18	0.20	1.60	1.16
t_2	1.18	0.77		.07
t_3	0.08	0.10		

This ends our immediate task but certain remarks may be added either to encourage the hoped-for convert to amateur optics or to add to the store of practical knowledge of users of astronomical telescopes.

First, I suggest that a focal length of three-quarters of an inch would be better for an initial trial, as rather easier to make than either high or low powers. Second, I wish to refute the general supposition that a plane surface is more difficult to make than a curved one. There is no more difficulty in securing a surface of zero curvature to one one-hundredth than a like accuracy in the case of any other named curvature; it is only the fact that plane surfaces are so often employed in oblique reflection, where a precision much greater than that named is necessary, that gives rise to the belief. In the flat surfaces of the oculars described the maker need have no hesitation in making them, with appropriate handles, just as he would the convex ones.

In certain cases a field as large as possible is very desirable, as in comet seeking for example. Nothing else known to me is as good in this respect as an ocular which I designed at the request of the late Mr. McDowell and of which, I believe, he or his successors have made many.

I venture to add the following under the impression that the Herschel wedge is not nearly as much used as it should be. With it Venus, so unsatisfactory an object in a dark, or darkening sky, is a delightful study. Then the moon also, except when a rather slender crescent, is much pleasanter to view with this accessory. Ordinarily this object is so brilliant that the pupil of the eye is contracted so that only part, perhaps a small part, of the objective is effective, which may be the cause of a prevalent impression that the moon is too easy an object to afford a test for the excellence of a telescope.

Yale University, New Haven, Connecticut.

Part V.

Grinding and Polishing Machines

Whether one chooses to use a machine or not—unless working on disks more than about 16 inches in diameter where it is virtually imperative—is a question the amateur may decide for himself. There are those who, like Ellison, prefer to work by hand, and others whose vote will be cast for the machine. Excellent work may be done by either method.

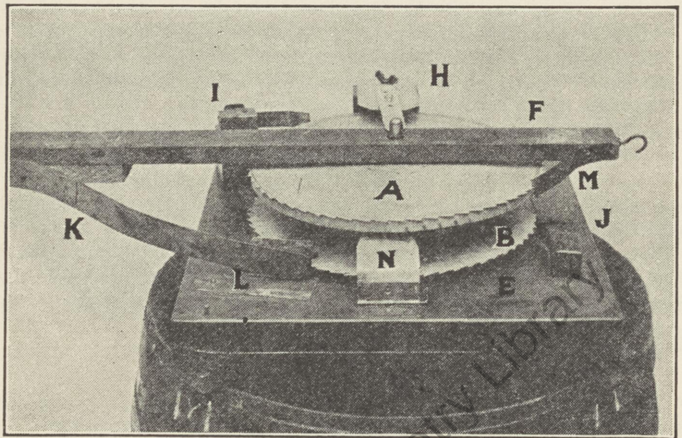


FIGURE 1. LEE'S MACHINE

Many, however, actually enjoy designing and constructing a machine, and especially the satisfaction of sitting back and watching the automaton of their own creation accomplishing the work. In the present chapter several machines are briefly described—briefly, because the accompanying illustrations all but describe them. The worker who is handy enough to build a practical machine will himself be able to supply the minor mechanical details when given a hint by a drawing or photograph, and will perhaps enjoy the job the more if not too minutely instructed. It will prove possible to vary the details to suit one's own ideas and requirements, and there is nearly always room for improvement.

The simplest automatic machine which has come to our attention was constructed in 1927 by John C. Lee. This was described by Mr. Lee, in the *Scientific American*, August, 1927, as follows:

"It is probably unsportsmanlike for the amateur telescope maker to consider anything in the way of a machine to help him with the tedious work of

grinding and polishing his mirror. There are, however, renegades, and I am one of them.

"The pictures, Figures 1 and 2, show a simple form of machine which almost anyone could make in a day or two from material taken from the scrap heap. One of them shows the machine ready for operation, and the other one shows the separate parts.

"What seems to be a novel feature in this machine is the immersion of the rubbing surfaces in the grit or rouge mixtures, thus eliminating the necessity of constant attention.

"Most of the sheet metal work is made of number 22 B. and S. gage galvanized iron.

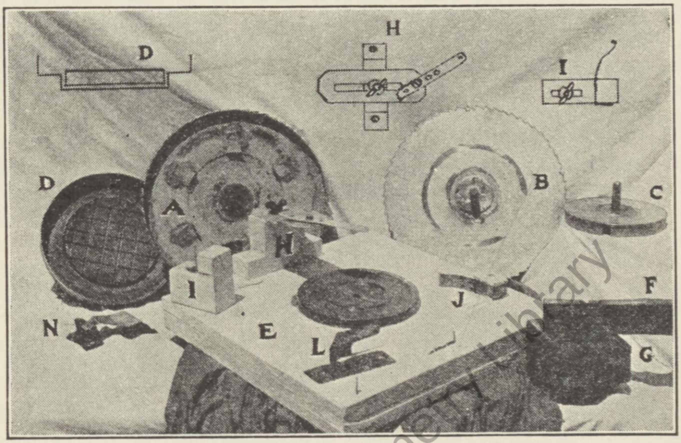


FIGURE 2. PARTS OF LEE'S MACHINE

"The lettered parts are as follows:

A: Disk with 63 teeth cut in the edge to form a ratchet wheel. On the lower side is soldered a dust rim and six clips to grip the mirror holder *C*.

B: Similar to *C* except that it has 60 teeth and the six clips are on the upper side to hold the pan *D*. The lower side has rigidly fastened to it a spindle for insertion in the base *E*.

C: Cup-shaped mirror holder with a rigid spindle, which when assembled passes through disk *A* and connecting rod *F*. The rim on the inside has three pieces of rubber, spaced at regular intervals and fastened with shellac. Over the mirror is placed a disk of rubber (old inner tube) to serve as a cushion.

D: Recessed tray for holding the lap and grinding or polishing mixture.

E: Wooden base with central hardwood turntable.

F: Connecting rod for transmitting a reciprocating motion. (60 strokes a minute is a satisfactory speed.)

G: Wooden block to be fastened to the face plate of a lathe or other rotating device to impart motion.

H: Adjustable guide.

I: Adjustable pawl for turning disk *A*.

J: Pawl to prevent backward motion of disk *B*.

K: Pawl for turning disk *B*.

L: Guide for controlling pawl *K*.

M: Pawl to prevent backward motion of disk *A*

N: Stirring device of hard wood, mounted on a flexible and readily detachable arm.

"An inspection of the pictures will show that the machine is capable of performing all the ordinary hand strokes of grinding and polishing. A practically straight stroke can be imparted by substituting a long arm in place of the short one *H*.

"Pressure is obtained by clamping weights on connecting rod *F*. Fifteen pounds is sufficient up to the finest polishing, when no weight is desirable.

"The barrel on which the machine is mounted serves as an element of safety in case there is a tendency to grip; in this event it will tip. Gripping can be eliminated during the grinding by the use of a grooved lead lap in place of glass.

There is an advantage in adding to the grinding mixture something to increase the density as well as the gravity of the liquid, such as sugar or other inert substance, and thus retard the precipitation of the grits during the grinding process. The stirring device alone is not sufficient for the most satisfactory results.

The laps are raised and lowered in the recessed tray *D* by means of rubber disks, and a thick rubber band is placed around the edge of each lap.

"One 6-inch glass mirror was ground, polished and figured on the machine without any hand rubbing. A 6-inch quartz mirror was made on it up to a polished sphere, and the final figuring was done by hand.

"The device is most satisfactory during the fine grinding and polishing. If a mirror has been overcorrected and is in the form of a hyperboloid or some other monstrosity, it is only necessary to put in a suitably trimmed lap and let the machine run by itself until the desired results are attained."

The Editor has had the privilege of watching Mr. Lee's machine, described above, in action; also of inspecting a creditable quartz mirror it produced. Though simple both in construction and operation, the machine performed steadily and could be left running for long periods without attention.

Four different machines are depicted in R. W. Porter's composite sketch reproduced in Figure 3. The first, labelled *A*, is a three-cornered German machine he used at the Bureau of Standards in Washington, while employed on optical work during the World War. Compounding the crank throws on the two rear crank shaft permits all kinds of strokes, straight, elliptical or

figure eight, on the nearer spindle which carries the work and lap. Machines of this general type are used in the famous Carl Zeiss Works at Jena, Germany.

The second machine in Figure 3, labelled *B*, was designed and constructed by Porter and is the machine he regularly uses. This is a bench machine with a capacity up to 12-inch disks. The crank arm carries a spindle which transmits, through bevel gears at the crankpin to a worm and worm gear at the pin which engages the mirror, a slow rotation of the work in a direction

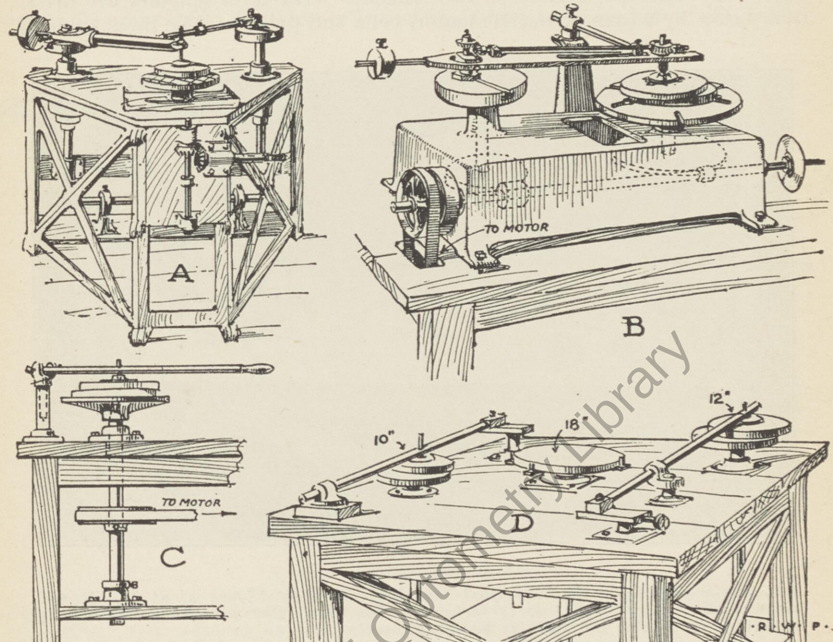


FIGURE 3

Machines for grinding and polishing, described in the text. The beginner frequently labors under the belief that a machine is a necessity if really good work is to be done. This belief is entirely without foundation. Ellison, whose hundreds of high grade mirrors may be found the world over, works by hand and states that he has completed a mirror, from the blank to polishing and figuring, in six hours, a feat which of course requires skill and experience in addition to physical endurance. A machine nevertheless appeals to the mechanically minded, and the sketches shown above are therefore inserted largely as a source of ideas for designs.

opposite to that of the lap below. The machine has polished about 100 mirrors of varying diameters and has been found entirely satisfactory. The sheet iron disk on the right hand end of the worm shaft is for slicing glass.

The third sketch, *C* in Figure 3, depicts the elements of a simple vertical spindle and hand lever, as originally sketched by G. H. Lutz. The handle is universally pivoted at the fulcrum end, and during use it is given a hand motion backward and forward. For disks of 6 inches or more the lap should be revolved slowly, but for small work like eyepiece lenses it may turn at 700 to 1000 R.P.M.

The fourth machine, *D,* was redrawn from a rough sketch by F. M. Hicks. The drawing depicts schematically the three spindles built and used by the "Amateur Telescope Makers of Los Angeles." All three spindles are driven from below by means of electric motor, belts and pulleys. The three grinding

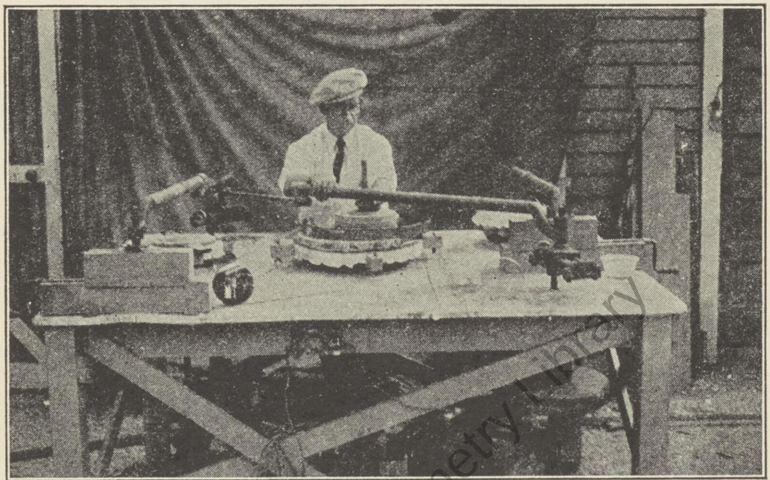


FIGURE 4

A photograph of the three-part machine shown in Figure 3, at D. It will accommodate disks from 4 to 18 inches in diameter. The man shown is merely adjusting the levers, the machine being automatic.

tables will take, respectively, 10, 12 and 18 inch disks. The table is of wood, heavily braced and very solid. Figure 4 is a photograph of this table and its attachments.

Finally we come to the Ritchey type of machine designed and used by Professor G. W. Ritchey for grinding, polishing and figuring the 60-inch mirror, shortly previous to 1904, at the Mt. Wilson Observatory. This was described in "Smithsonian Institution Contributions to Knowledge," Volume 34, a work which is now entirely out of print, and rare. The part of this work which describes his machine is quoted below; machines closely similar were used in 1916 in making the 100-inch mirror at Mt. Wilson Observatory (Figure 10), and in 1926 at the Paris Observatory in his experiments on

cellular mirrors. (See the Miscellany.) The fact that he has seen fit to embody the same principles in three successive machines is evidence that the design has proved satisfactory. Though this type is primarily intended for large disks, those who wish to design machines of various capacities will find a close study of it well worth while. The four illustrations, Figures 6, 7, 8 and 9, are reproduced from prints made from the original negatives, and were supplied through the courtesy of Professor S. B. Barrett, Secretary of Yerkes Observatory. Professor Ritchey's description follows:

"The grinding and polishing machines used by the writer are somewhat similar in principle to Dr. Draper's machine, shown in Figure 25 of his book,

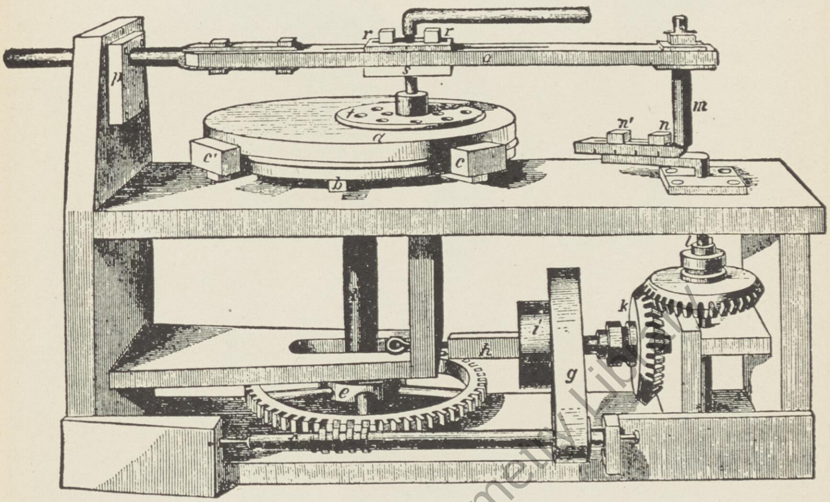


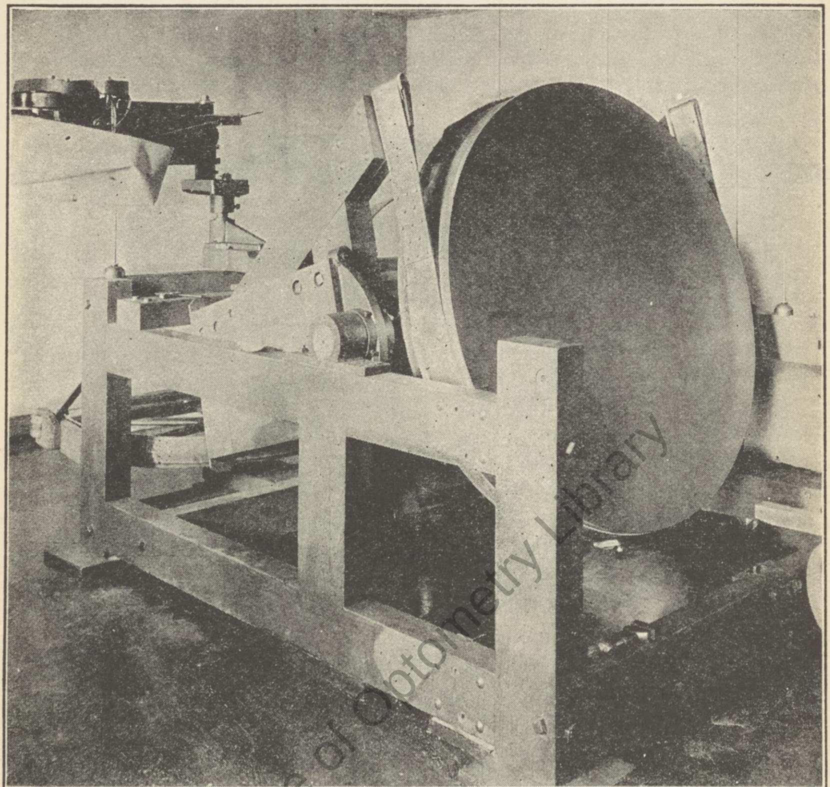
FIGURE 5, THE ANCESTOR

This is the old Draper machine to which Professor Ritchey refers in his description. Older still were the machines of Lassell and Lord Rosse; while Smith's "Compleat System of Opticks," 1738, contains an illustration of Huyghen's machine. Thus, the grinding and polishing machine is about as old as the reflector itself.

but are more elaborate. I shall describe here the machine used in making the 5-foot mirror, both because it embodies most of the essential features of a grinding and polishing machine, and also because it is the only one of my machines of which I have a series of photographs for illustration. A good idea of this machine may be gained from the views of it shown in Figures 6, 7, 8 and 9.

"The massive turntable upon which the glass rests consists of a vertical shaft or axis 5 inches in diameter, carrying at its upper end a very heavy triangular casting, upon which, in turn, is supported the circular plate upon which the glass lies. This plate is of cast iron, weighs 1800 pounds, is 61

inches in diameter, is heavily ribbed on its lower surface, and is connected to its supporting triangle by means of three large leveling screws. The surface of the large plate was turned and then ground approximately flat; two thicknesses of Brussels carpet are laid upon this, and the glass, with its lower surface previously ground flat, rests upon the innumerable springs formed by



Courtesy of Yerkes Observatory

FIGURE 6

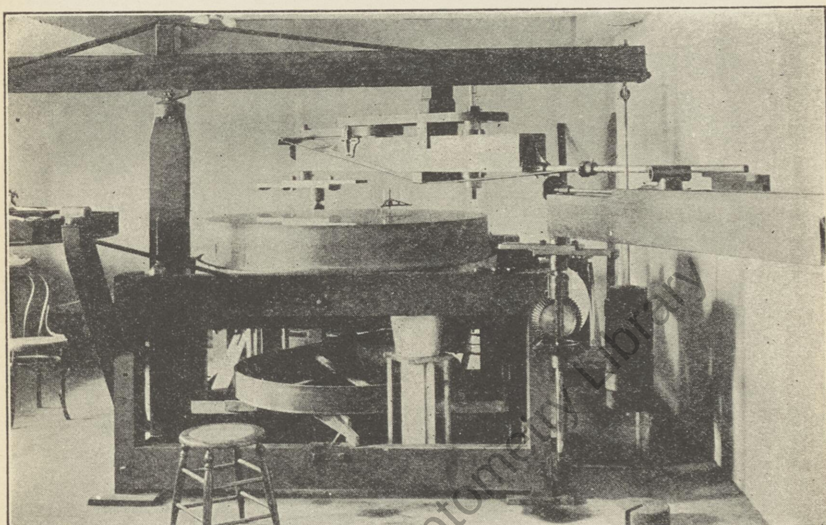
The Ritchey machine used at Yerkes Observatory for making the 60 inch mirror destined for Mt. Wilson Observatory. The mirror is shown tilted up, ready for testing.

the looped threads of the carpet. No better support for a glass during grinding and polishing could be desired.

"Three adjustable iron arcs at the edge of the glass serve for centering the latter upon the turntable, and prevent it from slipping laterally.

"The entire turntable, with the heavy frame of wood and metal which supports it, can be turned through 90 degrees about a horizontal axis, thus enabling the optician to turn the glass quickly from the horizontal position which it occupies during grinding and polishing, to a vertical position for testing. This is shown in Figure 6.

"The turntable is slowly rotated on its vertical axis by means of the large pulley below (Figure 7). This rotation is effected by means of belting from the main vertical crankshaft on the east end of the machine; this shaft is well shown at the left in Figure 8. At the upper end of this shaft is the large crank, with adjustable throw or stroke, which moves the large and strong



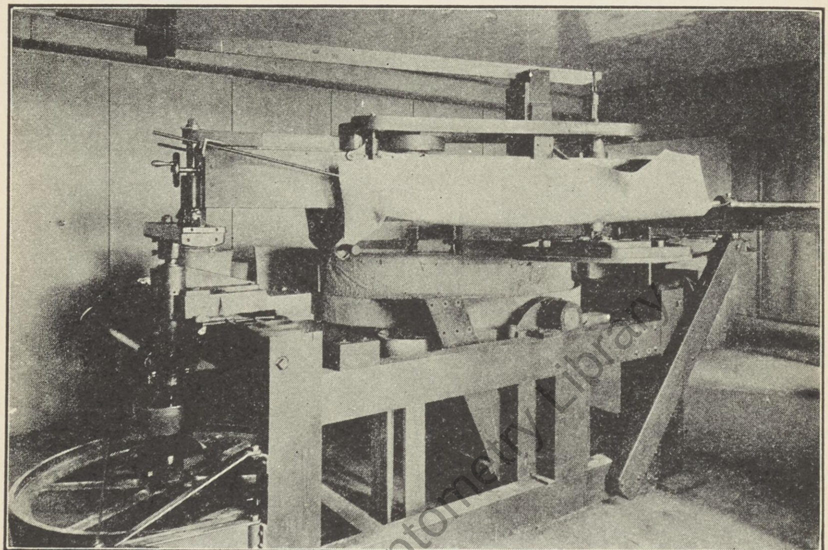
Courtesy of Yerkes Observatory

FIGURE 7

Another view of the machine shown in Figure 6; also Figures 8 and 9. The large lever across the top extends about 18 inches farther to the left, out of the illustration. Here the grinding tool, a part of which shows, is attached to it by means of a threaded screw which is equipped with a hand wheel permitting vertical adjustment.

main arm to which the grinding and polishing tools are connected, and by means of which they are moved about upon the glass. This I shall always refer to as the main arm. It is a square tube of oak wood, and is strong enough to carry the counterpoising lever shown in Figure 8, and the weight of any of the grinding tools, when fully or partially counterpoised. This main arm also carries the system of pulleys and belts by which the slow rotation of the grinding and polishing tools is rigorously controlled; these, and the manner in which this rotation is effected, are well shown in Figure 8.

"The west end of the main arm consists of a strong steel shaft which slides in a massive bronze swivel-bearing which corresponds to the 'elliptical hole in the oak block p' of Dr. Draper's machine (see his Figure 25). But this bearing is not stationary as in Draper's machine; it is not only mounted on a long slide (which I shall refer to throughout this article as the transverse slide), so that it can be slowly moved for several feet across the west end of the machine by means of a long screw, but this bearing and slide are carried upon a secondary strong arm, which is moved by a secondary crank at the southwest corner of the machine. Unfortunately there is no photograph which shows this part of the machine as it appears when in use; Figures



Courtesy of Yerkes Observatory

FIGURE 8

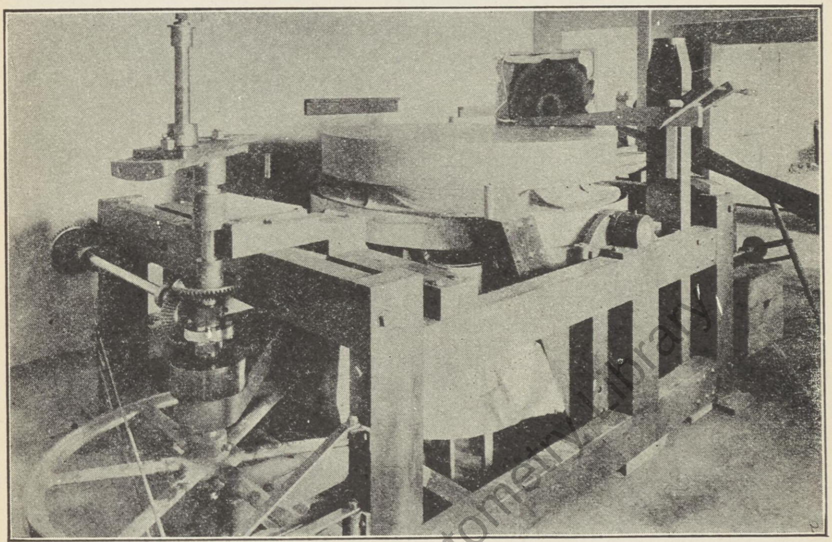
6 and 7 show the secondary crank well, but the secondary arm is shown swung around with one end resting on a bracket on the wall, in order to have it out of the way.

"The arrangement of the west end of the machine is the result of experience with several machines, and is found extremely serviceable and convenient. The long transverse slide on the secondary arm allows the grinding and polishing tools to be placed so as to act on any desired zone of the glass, from the center to the edge; and this setting can be changed as desired while the machine is running. The secondary crank, which turns at the same speed as the large one which drives the main arm, enables the optician to change as desired the width of the (approximately) elliptical

stroke or path of the tool with reference to the length of this stroke; this change is especially desirable when figuring the glass; it is, of course, impossible when only one driving crank is used.

"I regard the transverse slide, or something equivalent to it, as absolutely necessary to the success of a grinding and polishing machine; it will be noticed that its purpose corresponds, in some measure, to that of the long slot in the main arm of Draper's machine. I have used both arrangements and have found the transverse slide to be far more effective and convenient in use; its use will be described in the chapters on grinding and polishing.

"The secondary crank, while very desirable and convenient, for the reason



Courtesy of Yerkes Observatory

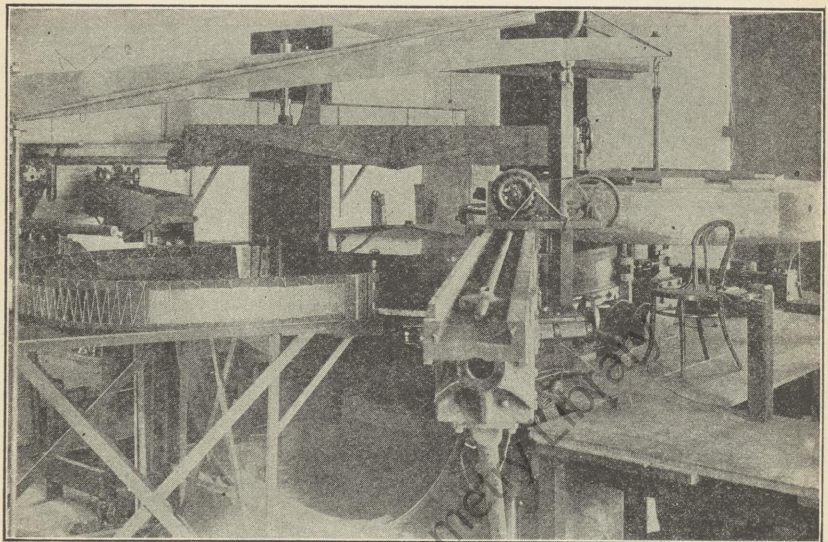
FIGURE 9

The attachments are shown swung out of the way, and equipment for edging the mirror is in use as it slowly rotates. Generally a disk of soft steel with carborundum and water, is used for this purpose.

given above, is not indispensable; I have used several smaller machines which have given good results without it.

"The manner in which the grinding and polishing tools are connected to the main arm is shown in Figure 8. A vertical shaft, 1⅜ inches in diameter and 24 inches long, both rotates and slides (vertically) freely in bronze bearings attached to the main arm. The grinding and polishing tools are connected to the lower end of this shaft through the medium of a large universal coupling—a gimbal or Hooke's joint—with two pairs of horizontal pivots at right angles to each other; this allows the tools to rock freely in

all directions in order to follow the curvature of the glass. The tools are lifted, for counterpoising them, by the lever above (see Figure 8), through the medium of the vertical shaft and the universal coupling. In the case of very massive grinding tools of moderate size, like that shown in this illustration, the universal coupling is connected directly to the back of the tool; but in the case of all large tools which are to be used for fine work this connection is made through the medium of a system of bars and triangles, so that the tools are counterpoised without the slightest danger of changing their shape. A small coupling with ball bearings at the upper end of the vertical



Courtesy of Mt. Wilson Observatory

FIGURE 10

The 100-inch mirror for Mt. Wilson Observatory being finished by Professor Ritchey in the laboratory in nearby Pasadena. Compare the machine used with that shown in the previous four figures.

shaft allows the latter to rotate freely with reference to the link which connects it to the counterpoise lever.

"To recapitulate briefly: This method of connecting the grinding and polishing tools allows them to be controlled in all of the following ways simultaneously: (1) the stroke of the tool is given by the motion of the main arm; (2) the slow rotation of the tool is rigorously controlled by the belting above; (3) the tool is allowed to rock or tip freely by means of the universal coupling, in order that it may follow the curvature of the glass; (4) the tool rises and falls freely by means of the sliding of the 1⅜-inch vertical shaft in its bearings, in order that it may follow the curvature of the glass; (5) the

tool is counterpoised by means of the lever on the main arm, through the medium of the same vertical shaft and universal coupling.

"In Figure 7 is shown the large lever by which the 5-foot glass, which weighs a ton, is lifted on and off the machine, and by means of which, also, the large grinding tools are handled. One of the full-size grinding tools, weighing 1000 pounds, is shown suspended by the lever. The arrangements are so convenient that the optician alone can do all parts of the work."

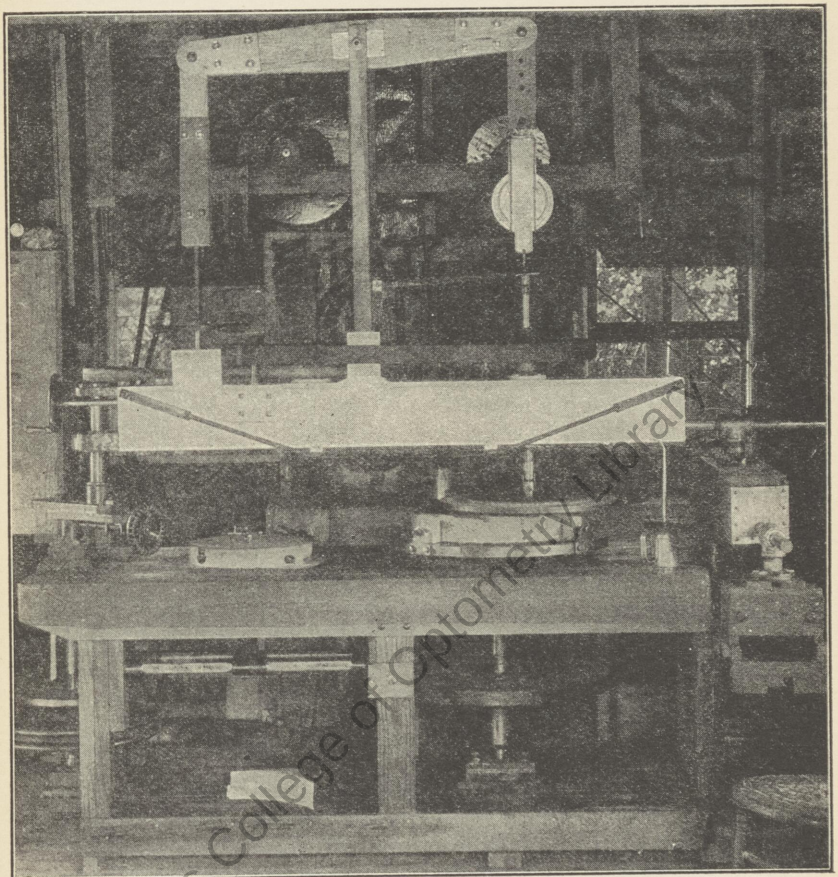


FIGURE 11

Henry H. Mason recently constructed this machine of Ritchey type, but smaller in size and with a few minor modifications. Its mechanism is plainly shown in the illustration.

Part VI.

A Serviceable Telescope Mounting from Discarded Automobile Parts

By Clarendon Ions

Reprinted by permission from *Popular Astronomy, February,* 1925.

While there is now a fairly complete literature available to the amateur, dealing with the construction of mirrors for reflecting telescopes, very little information of practical value can be gleaned regarding mountings.

As every amateur who has tried it will know, the securing of patterns and castings and the machining of parts for a rigid, yet smooth working, mounting with clamps and circles is a difficult and expensive undertaking.

It is therefore of interest that discarded Ford parts, obtainable almost for the taking at repair garages and junk yards everywhere, are perfectly adaptable to the construction of mountings to carry telescopes of any probable weight within the scope of amateur construction.

While this description will be confined to the subject of such a mounting, constructed by the writer, it may be appropriate to give the specifications of the telescope it carries, constructed at the same time, so that upon completion of the mirror the mounting was ready to be utilized in testing for figure at focus.

The mirror was ground from a disk of commercial plate glass $1\frac{1}{2}$ inches thick by 10 inches diameter, to a spherical radius of 144 inches, giving focal length of 72 inches, and was figured to a paraboloid of 2/3 the conventional correction of $2F + R^2/4F$, to compensate for distortion in the early observing hours, due to radiation of accumulated specific heat (Wassel and Ellison).

Polishing and figuring were done on a lap of rosin with 20 per cent beeswax (Fullan) and silvering by Ritchey's process, these formulae apparently working best in our southern climate.

Foucault's test with artificial star at center of curvature was used for the modified correction at each zone, later changed to test at focus in the mounting on actual stars.

A tube of 22-gauge sheet metal, 12 inches by 72 inches, was fitted to rotate in slip rings turned off from discarded automobile brake drums. A wooden counter cell with three adjusting screws was arranged to carry the mirror cell on a pivot with spring clamp, to permit rotating speculum if necessary to correct astigmatism due to axial stress or flexure in the glass (Draper and Maskelyne).

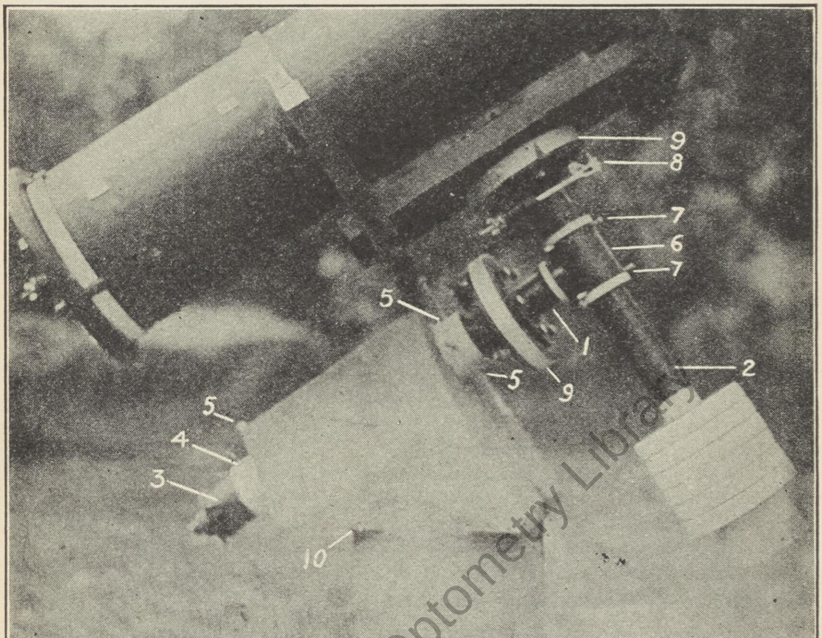
The reflected pencil was intercepted 10 inches inside focus by an elliptical silvered flat with adjustment provided for the reflection angles, as well as for decentering the secondary if necessary, to test for Herschelian aberration (Draper).

The weight of the finished telescope with its counterpoises carried by the hour axis approximated 196 pounds.

The annexed photograph-diagram will illustrate details of construction, and

it is worth noting that the somewhat clumsy-looking but easily constructed wooden cradle, carrying the tube suspension rings, was originally intended as a test frame, but has worked so well that it will not be discarded.

The automobile parts required consisted of two Ford rear axle assemblies, omitting differential parts, *i.e.,* axle housings (either right or left) with axles, hubs, brake drums and shoes, roller bearings and sleeves, rear spring perches and the necessary assembling nuts and bolts. The manufacturer's list on



Courtesy of POPULAR ASTRONOMY

FIGURE 1. THE DETAIL OF THE TWO AXES.

these parts new is $27.20, but with discrimination in selecting them, second-hand parts were secured at a fraction of this cost, in some respects superior for the purpose in hand to new ones. New axles, however, are recommended in all cases, and the two cost $3.00.

In addition to the automobile parts, a section of rolled steel well pipe, 3½ inches diameter (4 would do), 18 inches long; a section 2 inches long from the threaded end of a 2-inch pipe; and a malleable iron pipe tee, 2½ by 2 inches, were required.

The machining necessary to adapt the parts consisted of chucking one

axle in lathe and turning its central parts down to same size as the machined bearing parts. One hub was turned off to receive the 2-inch threaded pipe end (1 Fig. 1), which was cold pressed in place. One axle housing was sawed off above the bell-shaped differential case (2 Fig. 1), and reamed out to receive bearing sleeve. The other axle housing had its differential case turned off (3 Fig. 1) so it would pass through the $3\frac{1}{2}$-inch well pipe. The latter (4 Fig. 1) received four $\frac{3}{8}$-inch tapped holes (5 Fig. 1) on quarters at each end—likewise each $2\frac{1}{2}$-inch end of the tee (6 Fig. 1) was drilled and tapped for three 5/16-inch set screws (7 Fig. 1).

The assembly was made as follows: The section of well pipe was placed in a small roof-shaped wooden form, edges of form trued with plane, two wedge-shaped sides added, cut to angle of the local latitude, ends closed in, the whole inverted, leveled and form poured full of concrete encircling the section of pipe. Some wire netting had been placed as reinforcement and, before setting, a number of old bolts and rods were put in position to project. This made the concrete equatorial head, and when it had hardened, the form was knocked off and a circular metal form was placed in ground at suitable height and depth, filled with rock and concrete, and the equatorial head was placed approximately in the meridian over this form, its projecting reinforcement engaging the soft concrete at top of pillar-form, making a perfect union (10 Fig. 1).

It will be noted that the section of well pipe (4 Fig. 1) was so placed in its form that one set of tapped holes would be vertical and one set horizontal when in position. Two cup-pointed set screws were placed in vertical holes at south end, two placed horizontally at north end, for adjustment in altitude and azimuth, while two round-nosed cap screws were put in the complementary holes to act as guides on final adjustment. The long housing (3 Fig. 1) was slipped into place in this pipe and secured by the set and cap screws. At this point excellent preliminary adjustments were made by improvising cross wires and sighting on Polaris at transit and elongation through this housing. Brake shoes and spring perches were added to both housings.

The machined hub and nipple (1 Fig. 1) were assembled on undressed axle, brake drum bolted in place, tee (6 Fig. 1) screwed firmly on nipple, and the whole assembled in housing with bearings in the usual manner, this finishing the polar axis.

The machined axle was also assembled in the regular way on shortened housing (2 Fig. 1), which was slipped through the tee (6 Fig. 1) and secured by three set screws (7 Fig. 1), this permitting precise adjustment to make the axes perpendicular to each other. Carefully centered reversed sights through this housing upon a convenient wall or target, enable this adjustment to be made readily and with high optical precision. The projecting part of this axle received the counterweights.

Two small 5/16-inch yoke bolts (8 Fig. 1) were cut from old brake rods, threaded, attached to brake cam, run through spring perches and finished with wing nuts. These made perfect clamps, adjustable from free running disengagement, through any desired degree of friction, to a positive clamp. The faces of the brake drums (9 Fig. 1) were graduated in hours and degrees

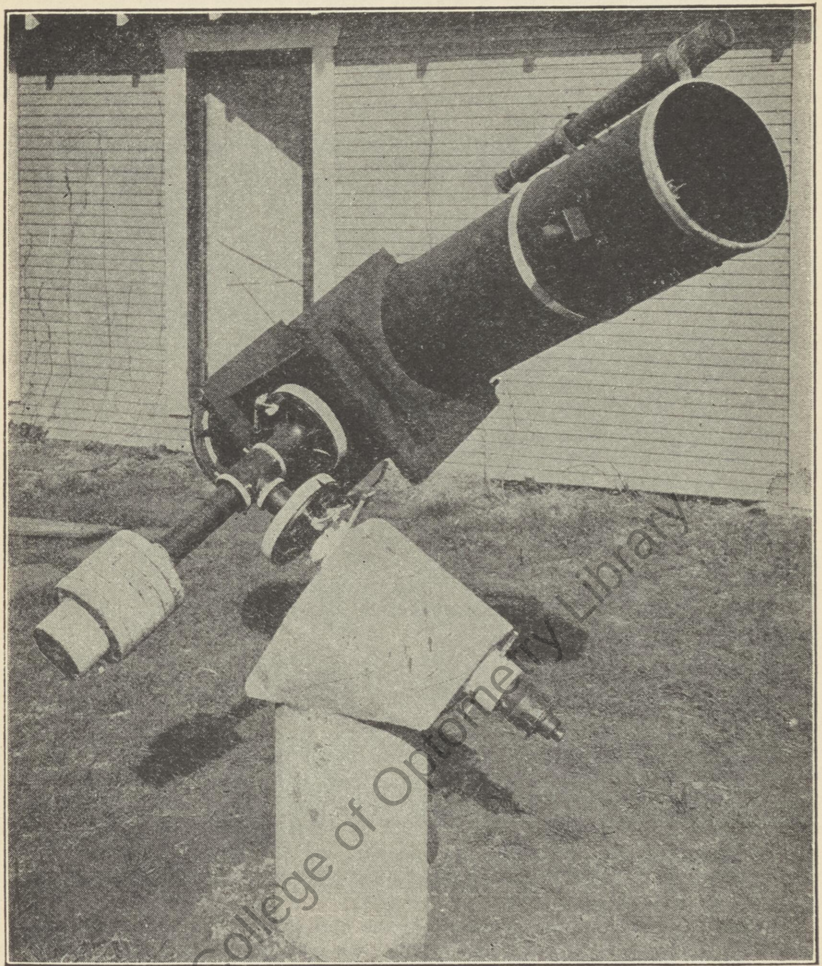


FIGURE 2. SHOWING THE EYEPIECE AND A FINDER, ATTACHED TO THE SIDE OF THE TUBE.

and provided with indicators, the latter being secured by small bolts passed through the bolt holes intended for the auto radius rods.

In the telescope illustrated, a wooden cradle is carried on the unmodified hub of declination axis, six bolts passing through brake drum, hub and base of cradle. This detail might be varied to suit construction of tube. It had been intended that a pipe flange should be carried on the declination axis, similar to placing of tee on polar axis, but the wooden cradle worked satisfactorily.

It will be noted that the essential merit of this mounting was its cheapness, the ease with which the parts could be obtained, its rigid yet smooth working capacity for carrying any weight required and the perfect clamps and circles provided by the brake parts.

Another noteworthy detail is the arrangement of set screws as suspension for both axes, whereby great delicacy of adjustment is secured without sacrificing strength or rigidity.

This same arrangement would be practical for an alt-azimuth instrument by the simple expedient of leaving the bell-shaped differential end of one axle housing in place, for base of azimuth axis, bolting it to floor or platform through the bolt holes provided in its original construction.

It should be understood that many of the details represent selection from one of numerous alternatives of construction. Further details of slow motion and clock drive remain to be worked out.

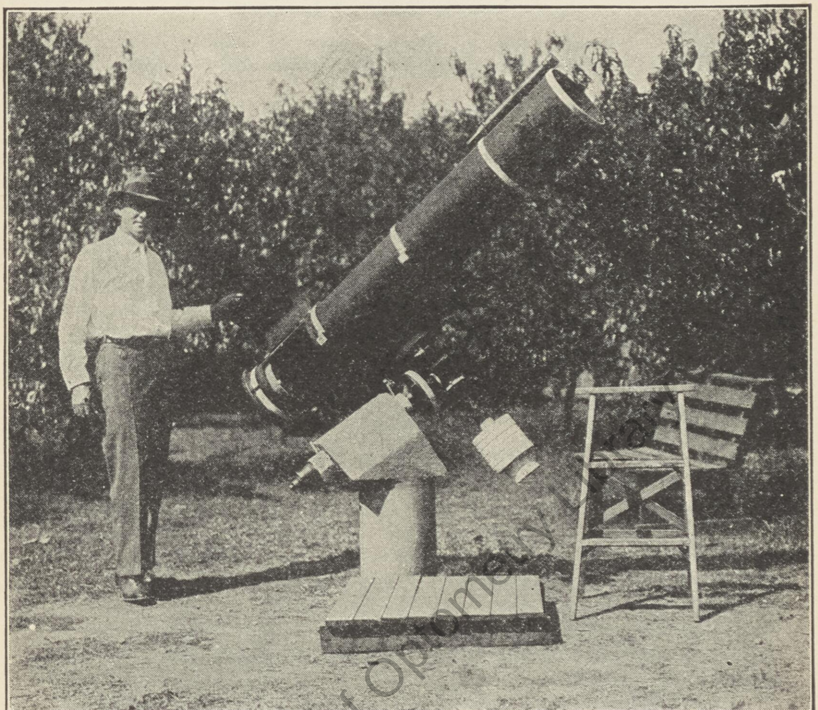
Therefore, the amateur following this plan will find unlimited room for improvements and modifications. The author of this description will appreciate letters from anyone pointing out any method by which the scheme can be bettered.

[Editor's Note: In a communication to the *Scientific American,* Mr. Clarendon Ions, now of Miami, Florida, makes the following comments concerning the telescope just described:

"No attempt was made to use circles for precision work nearer than 10′, and that was only for the visual finding of celestial objects in which there was no check in right ascension and very little in declination. Once set in declination, the telescope remained set.

"The mounting was perfectly steady, and entirely satisfactory for all visual requirements. For precision work, it would not only need slow motions not described in the article, but the roller bearings and their sleeves should be removed entirely, and ball bearings should be substituted for them, with the axle carrying the cones and the housing carrying the races. Excellent ball bearing assemblies, admirably adapted to this purpose, may be picked up at the auto wrecking yard.

"In the Ford car the inward thrust of the rear axles is carried on the axle pinion of the opposite axle, the two inside axle ends being separated by only the thickness of the small fiber thrust disk. However, in adapting this equipment to the telescope mounting, the corresponding thrust must be carried on the hub. I put in a small ball race to take the thrust, and it worked smoothly and perfectly."]



Courtesy of Popular Astronomy

Figure 3. MR. IONS AND HIS REFLECTING TELESCOPE, SHOWING THE PRINCIPAL MIRROR.

Part VII.

A Telescope That Anyone Can Make

By John M. Pierce
Of the Telescope Makers of Springfield

A practical telescope can be readily made by anyone having a little mechanical sense and a few carpenter's tools. The cost is trifling, less than $10.00.

The Newtonian form of reflecting telescope (See Fig. 1, page 167), is a very practical instrument and is of simple construction. It consists of a *speculum* or concave mirror (A), fixed at one end of the instrument. Light from a distant object falls upon the concave surface and is reflected to a focus which would be at F if it were not for the small flat mirror or *diagonal* (C) which reflects it to F′, where it may be more conveniently received into the eye through the *eyepiece* (D) through which the observer looks.

You will notice that the light does not pass *through* either of the mirrors, but is reflected from their surfaces. This fact permits us to use ordinary plate glass for making the speculum, instead of the expensive optical glass which is used in lenses.

We will consider the different parts of the telescope in detail. Directions will be given for making a 6-inch mirror of 50-inch focus.

The Speculum or Mirror

Provide the following:

2 disks of pressed or polished plate glass 6 in. in diameter and 1 in. thick.
1 pound No. 80 carborundum grains.
¼ pound No. 280 carborundum (also called "one minute").
¼ pound No. 400 carborundum (15 minute).
¼ pound No. 600 carborundum (60 minute).
¼ pound fine optician's rouge.
5 pounds black, Wilmington pitch. (If you cannot get pitch, use rosin.)
A bottle of turpentine.

A speculum must be at least ⅛ its diameter in thickness or else it will actually sag under its own weight sufficiently to destroy the image formed. Its working surface is to be hollowed out to a curve whose radius is twice the length of the focus desired.

To grind the speculum: Select the least perfect of the two pieces of glass and cement it to the corner of the work-bench by heating some pitch, pouring a little on the bench and setting the glass in it. When set, sprinkle the glass with a little coarse carborundum and water and rub it with the other glass disk. Use a short, straight, forward-and-back motion, and as you work, walk back and forth around the corner of the bench, also turning the glass in your hands between strokes, so that the grinding will take place in all directions across both glasses.

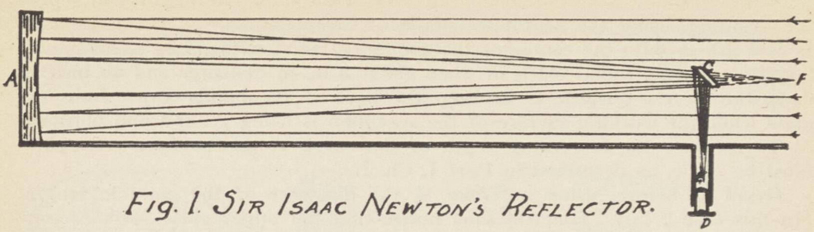


Fig. 1. Sir Isaac Newton's Reflector.

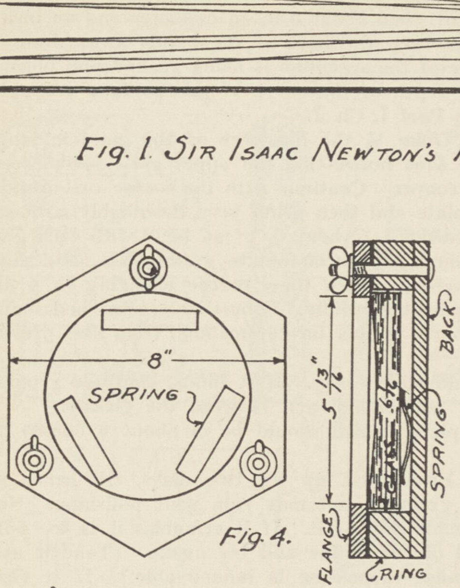


Fig. 4.

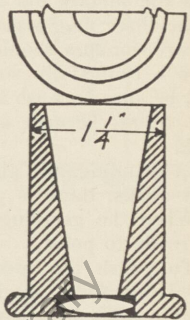


Fig. 7.

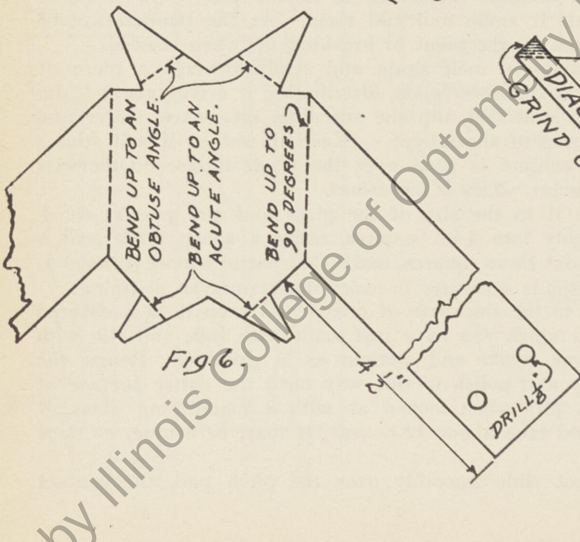


Fig. 6.

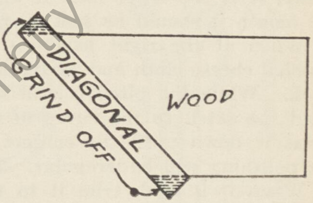


Fig. 5.

When this side is ground evenly all over, wash it off thoroughly and repeat the grinding, using the next finer grade of carborundum. A wooden handle is now attached to the center of the ground surface, with pitch. This handle may be a simple, round block of wood about 3 in. in diameter and an inch or more thick. Its purpose is to keep the heat of the hands away from the glass while the working surface of the speculum is being ground and polished.

To measure the increasing depth of the curve of this surface a template must be made, as described in Part I, Ch. I.

Grind as before, using a stroke ⅓ the diameter of the glass in length. (In this case 2 in.) You will soon notice that the upper glass becomes concave while the lower becomes convex. Continue with the coarse carborundum until the surface fits the template and then grind very thoroughly with each of the three finer sizes in succession. (About ¾ of an hour with each grade of carborundum should be enough.) The 60-minute grade (No. 600) should leave a beautifully smooth surface. Each time, before changing to a finer grit, be sure to wash the equipment carefully. Otherwise a scratched surface may result, because a few coarse grains have remained from the previous work.

In grinding, the glass should slide easily. If it binds, continue grinding. If it sticks, there is probably not enough grit between the glasses.

When the grinding is complete (which should be in about 6 hours) you are ready to polish.

To polish the speculum: First wash up the two disks, the bench and *everything,* for a single stray grain of grit may ruin your polishing. Next, test the pitch by chewing a small chip of it. If it crumbles it is too hard; melt it and stir in a spoonful of turpentine and try again. (Take it away from the fire to do this, because turpentine is inflammable.) If it chews easily, it is too soft; melt it again and add rosin. At the temperature of the mouth it should be just on the point of breaking up when chewed.

When at the right hardness, melt again and strain through a piece of doubled cheese cloth and on the lower glass, distributing it evenly about ¼-in. thick. While the pitch is still soft, dip the speculum into warm water and mold the pitch to the curve of the mirror. (Keep it wet or it will stick.) Press it down until the contact is good over the whole mirror. Otherwise the polishing will be irregular. *This is important.*

When it is cold, trim it to the size of the glass and cut grooves so as to divide the pitch roughly into 1-in. squares, using a sharp knife and a straight-edge. In laying out these squares, make the central square off-center, as in Fig. 3, page 169. This is necessary in order to obtain even polishing.

Mix rouge and water to the thickness of cream and keep it in a covered jar. Paint the pitch pad which you have just made with this, and rub with the mirror, using the same stroke and motions as in grinding. Renew the rouge whenever necessary and polish in this way until the entire surface of the mirror is free from pits when looked at with a magnifying glass or reading glass. This should take about 12 hours. It may, of course, be done in several spells.

If the mirror does not slide smoothly over the pitch pad, the contact

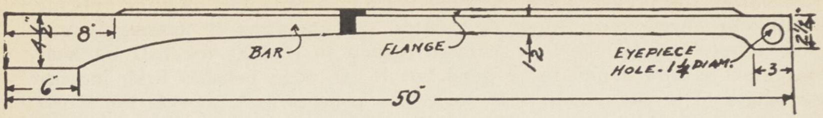


Fig. 8.

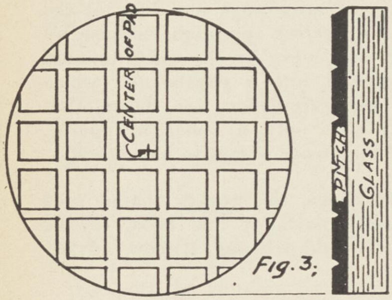


Fig. 3.

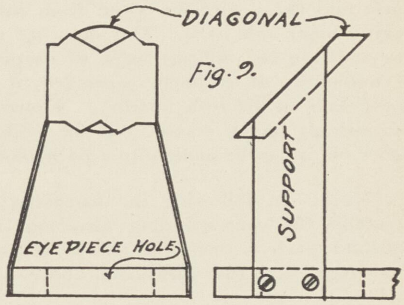


Fig. 9.

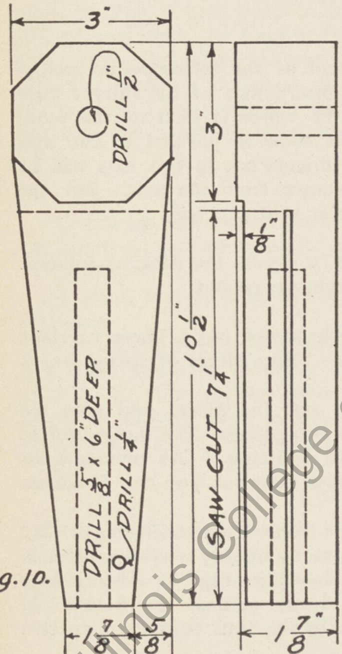


Fig. 10.

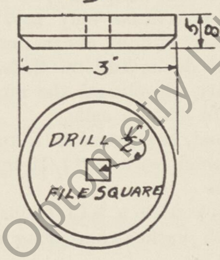


Fig. 11.

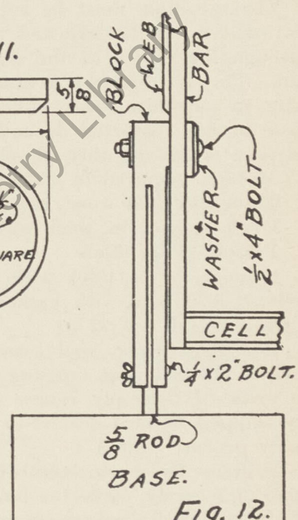


Fig. 12.

between the two is poor. If it does not improve after a few minutes' rubbing, weight the mirror with 40 or 50 pounds, first painting it thoroughly with fresh rouge, and let the two surfaces remain in contact for half an hour. If contact is now found to be good but if the edge polishes first, increase the length of stroke slightly. If the center polishes first, shorten the stroke.

If you have done your work carefully, your speculum should now have a curve which is a small section of a sphere, just as if one were to take a knife and cut a circular piece from the skin of an orange and look at the curved inner side of it. This does not make a *perfect* speculum, because we are omitting the difficult work of deepening our curve by the exact number of millionths of an inch, necessary to change it into a paraboloid (which does make a perfect mirror). However, my experience has shown that surprisingly good results can be obtained with only a spherical mirror. Later on, it can be made into a paraboloid if the owner wishes to improve it.

[Note: In following the foregoing instructions, the worker should read carefully the corresponding directions in other parts of this book, for he will find much in them that will be of use. For cold-pressing, Ritchey advises less weight than that mentioned above.—Ed.]

The Cell

The speculum must be supported at one end of the telescope in such a way that it can be adjusted to make the imaginary axis of the mirror pass through the center of the diagonal (C, Fig. 1) which is held at the other end. This is necessary because only rays that come in parallel to the axis come to a definite focus without aberration. Objects not in this axis will be more or less distorted depending on their distance from the axis. For the purpose of making this adjustment the mirror is held in a *cell.*

Material required to make a cell.

Three pieces of wood, hexagonal in shape, 8 in. across the flats, as follows:

1 cell ring, 3/4 in. thick with a 6 1/16-in. circle sawed out.

1 back, 3/8 in. thick.

1 flange, 3/8 in. thick with a 5 13/16-in. circle sawed out. Three carriage bolts, 1/4 in. x 2 in., with washers and wing nuts. Three pieces of spring brass, 1/2 in. x 2 1/2 in. x 1/32 in.

Use good, clear, well seasoned wood. Cut out the pieces and glue the back to the cell ring, crossing the grain of the two pieces. The flange should be made of three-ply veneer in order to avoid splitting. (As phonographs are shipped to local dealers in boxes made of this material, you can doubtless easily procure some.)

Drill for the 1/4-in. bolts (Fig. 4), and insert them from the back, driving them in securely. File the holes in the flange to fit loosely over the bolts in the cell. Bend the springs and assemble, as shown in Fig. 4. The springs should be strong enough to hold the mirror firmly against the flange. If they are too strong, they may bend the glass slightly, thus causing distortion of the image.

The Diagonal and Its Mount

Figure 1 shows how the converging rays of light from the speculum are reflected by a small mirror placed at an angle of 45 degrees to the axis of the speculum. This is the *diagonal* which throws the focal point to a more accessible place for easy observing.

Material required:

1 piece of plate glass, $\frac{1}{4}$ in. x $1\frac{1}{4}$ in. x 2 in. (Broken windshield is suitable; hunt around a public garage.)

1 wooden cylinder, $1\frac{1}{4}$ in. diameter x (about) 3 in. long.

1 piece of sheet zinc or brass, $4\frac{3}{4}$ in. x 9 in. x 1/32 in.

Saw one end of the wooden cylinder to an angle of 45 degrees and attach the plate glass to it with pitch, as shown in Fig. 5. Grind off the edges by rubbing them on a flat-iron or a glass surface with 1-minute carborundum (No. 280) and water until they are a continuation of the cylinder. Grind the exposed flat surface of the glass in the same way and then remove it from the wood and clean it with a knife and turpentine. Be careful not to scratch this face of the glass as it, and not the back, is to be the working surface of the mirror.

Cut out the support for the diagonal from the sheet metal, following the plan in Fig. 6 and bend to shape. The four small flaps turn up to hold the mirror while the long strips hold it at an angle of 45 degrees with the bar. Place the mirror in position and mark where the top flaps come on it. Grind a bevel on the glass at each of these places and bend the points of the flaps so as to hook over these bevels. The flaps should have to be sprung out in order to let the glass slip into position, and they should hold it firmly.

The Eyepiece

Eyepieces of various powers may be purchased if desired. An eyepiece for amateur use can be easily made as follows:

Get:

A small lens or magnifying glass of about 1-in. focus. A spool $1\frac{1}{4}$ in. in diameter.

Cut off the flange from one end of the spool and with a red-hot iron rod and some sandpaper, enlarge the hole to form a nest for the lens, as shown in Fig. 7. Use melted pitch to fasten the lens in place. The standard diameter for telescope eyepieces is $1\frac{1}{4}$ in. but any size spool available can be used if the eyepiece hole in the supporting bar, Fig. 8, is made to fit it.

Silvering the Mirrors

At your convenience you can be practicing silvering. This is a process that you may have to try several times before you learn. Practice on the diagonal, as it takes only a small amount of silver. Follow the directions in Part III.

The Supporting Bar

This member, which takes the place of the tube commonly used in reflecting

telescopes, holds the speculum in its cell, the diagonal in its support, and the eyepieces in their proper relations.

You will need:

A piece of wood $3/4$ in. x $4 1/2$ in. x 50 in., for the bar.
Another, $1/4$ in. x $1 1/2$ in. x 39 in., for the stiffening web.
2 flat-head wood-screws No. 10 x $1 3/4$ in.
4 round-head wood-screws No. 4 x $5/8$ in.

Saw the wood as shown in Fig. 8. Attach the diagonal support as shown in Fig. 9, using the small round-head screws. Be sure that the diagonal comes directly over the eyepiece hole. After silvering the speculum and diagonal, you should assemble the telescope and try it out. Assemble as follows:

Screw a temporary piece, about $3/4$ in. square x 5 in. long, to the back of the cell and flush with the edge. Clamp the cell in place on the supporting bar by this strip, using a C-clamp. Insert the eyepiece. Lay the telescope on a table or chair and focus it on some distant object by sliding the eyepiece in its hole and, if necessary, by moving the cell. When the cell is correctly placed, the eyepiece should project about 1 in. when it is focused on a distant object. When so located, fasten the cell with the No. 10 screws, first squaring it with the straight edge of the bar. Remove the clamp strip and saw off the projecting end of the bar.

This completes the telescope, which should now be taken apart and painted with a dead-black varnish. When dry, reassemble and collimate or line up the optical parts as follows: Stretch crossed strings over the eyepiece hole (eyepiece removed), the diagonal, and the speculum, in order to show their centers. Look through the eyepiece hole and bend the support of the diagonal until the three crosses are in line. Remove the crosses from the speculum and the diagonal and adjust the speculum by turning the thumb-nuts on the cell until the reflection of the strings over the eyepiece hole lines up with the strings themselves.

A brad, driven into the web near the eyepiece, and a screw at the other end will serve as sights for pointing the telescope. Adjust the sights until you find whatever object is aimed at, in the center of the field of the telescope. A sighting device is essential, as it is quite difficult to pick up stars without it.

The Mount

It is necessary to have a rigid support for a telescope of this size. To make the simple mount described you will need:

1 piece of hardwood $1 3/4$ in. x 3 in. x $10 1/2$ in.
1 carriage bolt $1/2$ in. x 4 in., with washer and nut.
1 carriage bolt $1/4$ in. x 2 in., with washer and wing-nut.
1 iron rod $5/8$ in. x 12 in.
Hardwood for the washer.

Make the block and the washer as shown in Figs. 10 and 11. Drill a 9/16-in. hole in the supporting bar at the point where the telescope balances

and assemble the block, washer and telescope, first rubbing the wearing surfaces with soap or paraffin. Adjust with the nut until the movement is easy but firm. The bolt should not turn in the block. If it does, paint the hole or put in a shim of paper. Paint all except the wearing surfaces with dead-black varnish.

A heavy base is necessary. Drill a hole in the top of a box about a foot square by 8 in. deep and stick the iron rod through it, 7 in. into the ground. Mix thoroughly 1 part of cement, 2 parts of sand and 4 parts of crushed stone or gravel. Now add just enough water to wet the entire mass. Fill the box and allow it to stand for several days. Then invert it, polish the rod with fine sandpaper and rub it with paraffin.

The telescope is now ready for use. Place the block on the rod and adjust it with the wing-nut in order to take up any looseness. Whenever you are through observing, lift the telescope from the rod and stand it in a safe place. Do not neglect to cover the silvered surfaces. Do not polish them or touch them.

Don't be content with your first instrument. The one described has been necessarily the simplest possible. Learn to "figure" your speculum, that is, make a paraboloid of it, so that it will take advantage of high powered eyepieces. Study different types of mounts and make an equatorial mount. Much of the pleasure of telescope making is in planning your own instrument and designing a suitable mount.

The following are some points learned by experience:

(1) Laps are rarely too soft—usually too hard.

(2) Saw out your facets with a hack saw. This is very easy.

(3) Before starting to polish, always put the lap into warm water for five minutes; and then start in immediately polishing. The immersion softens the lap and insures good contact.

(4) Keep good contact and you will have no zones.

(5) An emergency method of silvering; though the coat is not so heavy or tough as that obtained by the Brashear method it is serviceable and fool-proof. Clean the glass as usual. Prepare the following: One-quarter ounce silver nitrate in three-quarters glass distilled water. Add ammonia, drop by drop, until it clears entirely. Dilute one teaspoonful of formaldehyde with one-quarter glass of water and add to the silver solution. Immerse the mirror in this until a good coat is formed.

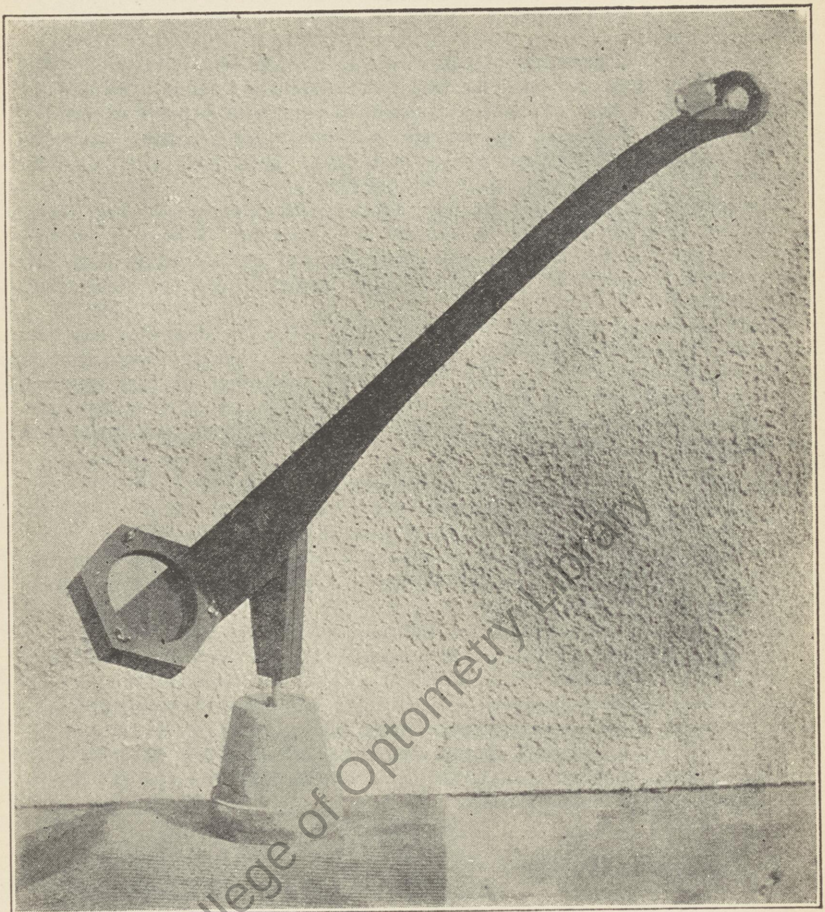


Photo by JOHN PIERCE

THE MOUNTING READY FOR INSERTION OF THE MIRROR AND THE EYEPIECE.

Part VIII.

The New HCF Lap

By A. W. Everest

The honeycomb foundation recommended for the HCF polishing tool is the pure beeswax variety sold by dealers in bee keeper's supplies under the trade name "medium brood foundation." This material runs seven or eight, 8 by 17 inch sheets per pound and costs about $1.00 for that amount. It is the little pyramids of wax that appear between each three adjacent cells, as the surface wears down, that form the "facets" of the tool.

To make the tool, lay a piece of HCF, trimmed to size, on the face of the mirror. Wrap a paper band around the mirror and pour in plaster of Paris to a depth of about one-sixth the diameter of the mirror, as shown in A, page 176. As the plaster sets, keep it pressed down with the hands to insure contact between HCF and mirror, and then level off by scraping across several diameters with a straight-edged knife.

Next, lay the tool, wax up, on the work bench and draw the blunt end of a table knife through each row of cells in all three directions and to a depth of one-sixteenth inch, as shown in *B*. This is necessary in order to allow the rouge to flow.

Finally, bevel off the circumference for about three-sixteenth inch with a sharp knife, and the tool is made.

Before starting to polish, set the tool in a pan of water for a few minutes to satisfy its affinity for moisture. Otherwise, it will remove all the water from the rouge around the edge.

The rouge recommended is Wellsworth Polishing Compound (Rouge) No. M309, procurable from branches of the American Optical Co., to be found in nearly all large cities. This polishes very fast but may be used with perfect safety without washing, as the HCF tool has no tendency to scratch.

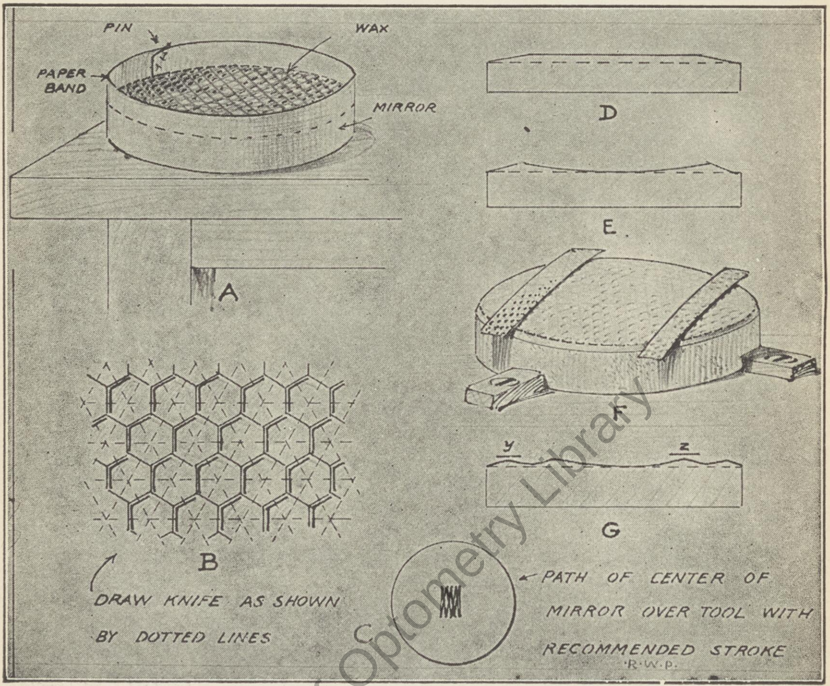
The stroke employed to bring the mirror to a complete polish may be the regular one-third, diametrical stroke described elsewhere in the book, but the beginner will probably have less trouble with the formation of zones if the stroke is shortened to one-fourth diameter and the center of the tool is made to travel over not only the diameter of the mirror, but also over several chords on either side of the diameter, as far as one-twelfth diameter off center. The complete cycle of strokes is shown in C.

Use a thick rouge paste for the first ten minutes of polishing. This does not polish as fast as when more water is used, but it wears the facets of the tool rapidly, which is at first desirable; for, since the tool is non-flexible, in contrast to pitch, it is necessary to depend upon this wearing action to bring it into perfect contact with the mirror.

Next, sprinkle water upon the tool until, after frequent trial, the point is reached where there is a pronounced drag; that is, when the fraction

between tool and mirror requires considerable muscular effort to overcome, and the facets are plainly seen through the mirror to be everywhere in perfect contact. This is the condition necessary for rapid polishing.

Plenty of pressure will further shorten the time required to bring the mirror to a complete polish and will have no ill effect if the thickness of the glass is equal to one-sixth of the diameter. A 6-inch mirror should be brought to a complete polish in about two hours.



Drawn by R. W. Porter

METHODS OF USING HCF

If any zones develop, they may be removed quickly by local polishing. Strips of HCF, one-half inch to 2 inches wide, as the occasion demands, are laid across the tool where needed to wear down the high spots, and "pressed" with the mirror plus about 5 pounds per square inch applied by the hands of the operator.

To avoid possible injury to the surface of the tool, these strips should be laid so that the centers of the cells on the under sides of the strips come over the facets of the tool. This precaution is, however, not absolutely necessary, as the tool is comparatively tough and will stand considerable abuse.

About the only thing to guard against is a slip of the mirror when placing it on the tool. This might result in shaving off an area of facets which would not come back to contact until the rest of the surface wore down.

To get back to local polishing, suppose you had the turned down edge shown in apparent section in D, it would require the removal of a considerable amount of glass to wear the mirror down to the point shown by the dotted line. Therefore, draw the knife-edge away until the surface has the apparent cross-section shown in E, when the glass to be removed will be located mostly in one zone.

This may be accomplished by polishing on two narrow strips of HCF as shown in F, starting with the straight, diametrical stroke and changing gradually to a slightly elliptical stroke to ease off the effect. The stroke must be parallel to the long dimension of the strips but the mirror will be turned in the hands. This will give something like G. Finally, moving the strips to *y* and *z* in G, will bring the surface approximately spherical; and a few minutes on the full sized tool will remove the remaining irregularities.

You will note in the illustration that when working on two zones, the strips are placed on opposite sides of the center. Otherwise the mirror would not balance. Also, since the weight is mostly on the inner strip, it will be necessary to use a little extra pressure on the mirror over the outside strip in order to equalize the action of the two strips.

With this strip method of local polishing it is possible to bring back to reason any shape imaginable.

Test often. One or two minutes on the strips is about as long as it is advisable to go, as the action is very rapid.

Although the final figuring can be accomplished by local polishing with special shapes, considerable experience is required; and for small mirrors, nothing is to be gained over the overhang method on the full sized tool, described elsewhere in the book.

Everest has modestly omitted to take due credit for his discovery of the honeycomb foundation lap which is already being tested by professionals. This is how it happened: On a hot night in the summer of 1926 he found his pitch lap rather inclined to run away, so he thought of coating it with beeswax, thinking this might hold it back. Being himself a bee keeper he started to melt up some of the only beeswax he had on hand, which happened to be a sheet of HCF. "Why not use the HCF just as it is," he asked himself, "without melting it up and painting it on the pitch?" To his surprise the tool started in to polish rapidly, but on first trial it gave to the mirror a figure which was described as "a combination of a badly turned down edge and a certain pectoral aspect of the Venus of Milo." This emphasizes the fact that the new material, as Everest states, is rather cranky for a beginner and must be used with circumspection, practice and possible persistence. However, a number of amateurs have subsequently learned the new technique. For polishing, HCF greatly hastens the work, but its greatest value comes as a method of local correction for badly figured mirrors. Instead of remaking

the pitch lap several times—a job which has always required so much pains and time that there always has been a temptation to let it go when the mirror was within sight of "good enough"—the worker with HCF finds it possible to change the lap in a jiffy, simply by moving the added strips or using a pair of shears to cut new strips of various widths. Beginners may be interested to know that there is plenty of room to make equally important discoveries in glass working, and while it is best to learn the orthodox methods at first, they need not be regarded as the tenets of a blindly accepted religion.

The following notes taken from a letter written by Everest supplement the instructions he has just given. "Even after the tips of all the little wax

THE DISCOVERER OF THE HCF LAP
From a pencil sketch by R. W. Porter.

pyramids are worn off so the plaster is touching the glass the tool keeps right on working and there is no tendency to scratch. At this point though, it is necessary to satisfy the plaster's affinity for water by keeping it thoroughly wet or it will have a tendency to absorb the moisture from the rough mixture.

"Coarse rouge or thick paste wears the tool away fast and polishes slowly. Fine rouge or thin paste wears the tool slowly but polishes the mirror very rapidly. The thick paste produces a loud grinding sound, but produces no friction, the granules of rouge merely rolling over the little hexagonal facets, wearing them down. This is useful at first in perfecting the contact or changing the surface of the tool slightly when ready to parabolize. Thin paste works very quietly, but with the proper mixture, mostly water, the friction between glass and wax requires considerable muscular effort to overcome, yet with no tendency to grab.

"And right here you make the sad discovery that it requires as much energy to polish by this method in one hour as it does in many by other methods. In other words, you don't get something for nothing. The sweat drops from your brow down on the tool just about fast enough to make up for evaporation. The amount of drag seems to give a good indication of the speed of polishing. Keep perfect contact at all times. If this is important with pitch, it is doubly so with HCF, and triply so if plaster of Paris is used for a base. Obviously, a single slip of the mirror may shave off quite an area of the wax cells, which will not come back to contact for a long time. With a little care this won't happen.

"If either the center or edge starts to polish first, a badly turned edge or deep hyperbola is sure to result, and therefore any such tendency must be corrected at the start. The mirror must be examined after a few seconds of polishing, or as soon as there is the faintest indication of where the polishing is taking place. Every surface I have tried started to polish at the edge, just the opposite of my experience with pitch. This was corrected by wearing away the outer portions of the tool slightly with thick rouge and an elliptical stroke around just inside the circumference of the tool. It will require very little of this juggling to get the surface of the tool in shape so that the mirror starts to polish evenly all over."

To the above, R. W. Porter adds: "While it is pretty well known that glass polishes more slowly on wax than pitch when the pitch facets are painted with hot beeswax, it is not the case when using comb foundation. Mr. Everest thinks perhaps it is the multitude of small hexagonal partitions that accelerates the polish. Certainly it polishes faster and will even show the imprint of the wax pattern on the glass, produced by the last stroke, unless the precaution is taken of letting up on the pressure before removing the glass."

HCF may be obtained in 1-pound cartons, from the A. I. Root Co., bee keeper's supplies; or from Dadant and Sons, both of which firms, according to Everest, put out the uniform product necessary for the telescope maker's purposes. Add to the dollar, parcel postage to your home address on a 3-pound package. The purchaser should specify "medium brood foundation," not HCF, which is a term we amateurs have applied to it.

Part IX.

SOLAR RESEARCH FOR AMATEURS

By George Ellery Hale, Sc.D.
Honorary Director, Mount Wilson Observatory of the Carnegie Institution

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CHAPTER I.

Sun-spots, Prominences and Flocculi

No chapters in the history of science are more inspiring than those that recount the discoveries of the amateur. Hampered, it may be, by lack of equipment, situated where conditions for research are not of the best, and often compelled to devote his best hours to other pursuits, the amateur, rising above all discouragement, has continued to pour a flood of new ideas and significant observations into the ever-widening sea of scientific knowledge. Many a great name is associated with a modest beginning, and many a discovery has been made with inexpensive apparatus. Intense interest and persistent purpose naturally bring their own reward.

The amateur thus has a great advantage over the perfunctory toiler, driven into research by someone who thought it might prove interesting, or lured on by a desire for fame or fortune. His eye is not fixed on patents or prizes, decorations or degrees. He works because he cannot help it, impelled by a genuine love for his subject and inspired by an irresistible influence, which he seeks neither to justify nor to explain. His reward lies in the work itself and in the hope that it may contribute something to the advancement of knowledge. If there is any means of deriving greater satisfaction from personal effort one must go a long way to find it.

It naturally follows that the world owes an immense debt to the amateur. His compelling interest, never flagging through the years, often leads to important advances. Thus, Schwabe, the apothecary of Dessau, recording sun-spots day after day for forty-three years with his small but "imperturbable telescope," discovered that their number waxes and wanes in the now familiar sun-spot period. Burnham, busy all day as a Chicago court stenographer, discovered nearly five hundred new double stars in his back yard with a 6-inch telescope. Huggins, in spite of the smoke and fog of London, borrowed instruments from the Royal Society and laid the foundations of astrophysics. Herschel, the organist of Bath; Barnard, the Nashville photographer; Lockyer, the War Office clerk; Bond, the watchmaker of Maine; Schumann, the Leipzig machinist; and many others, limited in time or means, have also left their names in the permanent roll of scientific discoverers. Darwin, Faraday and Rayleigh, though they gave their whole lives to research, were essentially amateurs, members of a guild devoted supremely to science and never to be confused with the idling dilettantes of the popular imagination.

While it is still possible in many fields to contribute to knowledge with the aid of small instruments of standard design, the wise amateur quickly takes advantage of favorable opportunities to enter untrodden territory. Thus while routine observations of variable stars visible with a small telescope are very valuable, the amateur who attaches a thermocouple or photo-electric cell to his equatorial can detect and measure much smaller light-variations than the eye can see, and thus discover new and important phenomena. The work

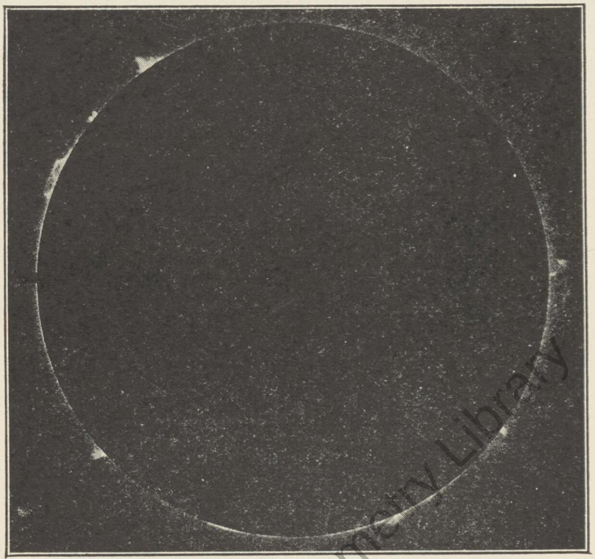

FIGURE 1

Solar prominences photographed in full sunlight with the spectroheliograph. Taken on Mount Wilson with the red hydrogen line (H a), September 21, 1909. (The Sun's disk was covered with a circular metallic screen).

of Stebbins is a fine illustration of this. A similar opportunity for entirely new work, due to the recent development of the spectrohelioscope, now exists in the field of solar research.

The Varied Interest of Solar Research

From whatever angle you look at it, the Sun offers interesting and remarkable subjects for investigation. Unlike most celestial objects, the brilliant and spectacular phenomena of its atmosphere are never twice alike, and the most violent outbursts of terrestrial volcanoes are tame affairs in comparison

with solar explosions. In order to gain any conception of the fantastic beauty of solar prominences it is necessary to see them in action. As Secchi has said in his book on the Sun, it is impossible to reproduce "the vivacity of color of these enormous masses, or to depict their rapid motions when they are shot by eruptions from the interior above the surface of the Sun. The best drawings are inert and lifeless when compared with the actual phenomena. These incandescent masses are vivified by internal forces which seem to endow them with life; they glow with intense brilliancy, and their colors are so characteristic that they enable us to determine spectroscopically the chemical nature of their constituent gases."

Such brilliant phenomena are striking enough in themselves, but their relationship to terrestrial disturbances makes them doubly important. If you

FIGURE 2

Slowly changing or quiescent prominence, 110,000 miles high. Photographed at Mount Wilson with the H a line, June 10, 1917.

are interested in radio, or the aurora, or terrestrial magnetism, you will want to learn the source of the electrified particles which are shot from the Sun into the earth's atmosphere, where they arouse the Northern Lights, initiate magnetic storms, affect radio transmission, produce powerful earth currents in telegraph lines, and sometimes puncture Atlantic cables. They are popularly supposed to come from sun-spots, but some of the largest spots produce no such effects and attention should be directed to the occasional eruptions, occurring on the disk near certain types of sun-spots, which the spectrohelioscope now renders visible.

If the nature and evolution of the stars appeal to you especially, remember that the Sun is the only star near enough the Earth to be studied in detail. To see the other stars as we do the Sun, to discern their huge disks, the spots on their surface, the flames in their atmosphere, it would be necessary to

approach them closely, and there is no prospect that any telescope, however powerful, will ever make this possible. The larger and more perfect the instrument and the better the atmospheric conditions, the smaller their needle-point images appear.

How fortunate, then, that one star is so near at hand! This neighboring object, our own Sun, is proved in a score of ways to be a perfectly typical star, similar in chemical composition, in size and in structure to millions of other stars in the remote distances of space. It is so near us that any telescope will show its disk and the spots that come and go on its surface. These and its other phenomena are most varied in character, constantly changing in number and in form, and suggesting problems of every kind for solution.

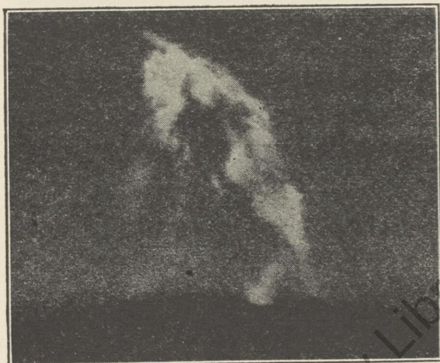

FIGURE 3A

Eruptive prominence photographed with the Kenwood spectroheliograph, Chicago, March 25, 1895, 10h 40m A. M. Height of prominence, 162,000 miles. Compare with Figure 3B.

Moreover, with the aid of a spectrohelioscope, the amateur will be able to observe, not merely the spectacular outbursts of the chromosphere and prominences encircling the Sun's circumference, but also the little explored region of the solar atmosphere now visible in projection against the disk. Here is a new field, open to amateurs, for discoveries of prime importance, which will aid in solving many puzzling problems of solar and stellar physics.

The Sun may also be regarded in still another aspect, the importance of which has recently been greatly enhanced by the revolutionary progress of physics and chemistry and the rise of the Einstein theory of relativity. In an article on "The Sun as a Research Laboratory"* I have recently pointed out some of the fundamental advances in physics which are the direct result of

* *Journal of the Franklin Institute*, July, 1927.

solar discoveries. As a matter of fact, the Sun is an immense furnace, with a surface temperature of about 6,000° C. and an internal temperature reaching millions of degrees, sufficient to strip the atoms wholly or partially of their electrons. Between this inner region and the visible surface of the photosphere the chemical elements recover most of their electrons, and we can observe their luminous vapors at various levels in the solar atmosphere under a wide range of conditions, which throw much light on the nature of matter. Thus the establishment of the fundamental principles of spectrum analysis, the discovery of the important element helium, and the first clue (through Lock-

FIGURE 3B

The prominence shown in Figure 3A, photographed at 10h 58m. Height of prominence, 281,000 miles.

yer's detection of the "enhanced" lines) to the modern theory of the constitution of matter, are all results of solar research. For other illustrations I must refer the reader to my Franklin Institute paper.

All of the solar phenomena I have mentioned are easily within the reach of the amateur. If lucky enough to have access to a small machine shop, he can build his own instruments and most of the optical parts. If not, he may purchase his entire equipment at moderate cost or buy only the optical parts and employ a local machinist to do any of the machine work that is beyond his own capacity.

Photography of the Solar Atmosphere

The classic discovery of Janssen and Lockyer in 1868, which made possible daily observation, in full sunlight, of the prominences previously visible only during total eclipses, aroused widespread interest in solar research. Fascinated by this advance, and dimly conscious of the boundless other possibilities of the spectroscope, I began solar work as a boy in 1883.

Six years later it occurred to me (as it had occurred to others) that by building up an image of the prominences upon a sensitive plate with the light of hydrogen or of calcium, I might photograph them without an eclipse. This

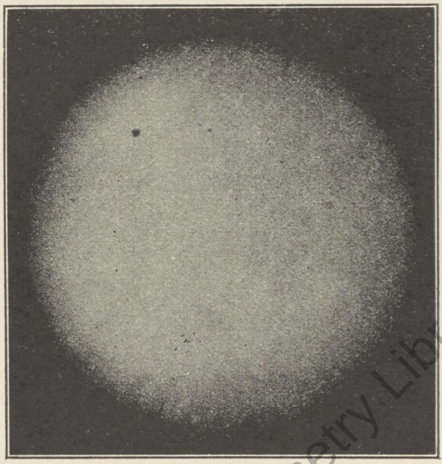

Figure 4

Direct photograph of the Sun, September 27, 1926. (Mount Wilson.)

I succeeded later in doing with a spectroscope, provided with a second slit instead of an eyepiece, through which a hydrogen or calcium line passed to the plate. When the slit of the spectroscope was moved slowly across the Sun, a complete image of all the prominences was built up on the plate by countless adjoining images of the narrow second slit. The bright light of the disk was excluded by a circular metal screen, and the encircling prominences were shown as distinctly as in photographs of total solar eclipses.

The next logical move (in 1892) was to try the same scheme for photographing the disk, where the calcium lines (H and K in the extreme violet) were known to be bright in many places. The spectroheliograph, as I had named the instrument, at once disclosed large bright clouds of calcium vapor (flocculi) in the solar atmosphere, which have since been extensively investi-

gated by Evershed, Deslandres, St. John, and others. These bright flocculi lie at a low level, and do not project above the Sun's edge (limb) as prominences. Later, at the Yerkes Observatory, we found it possible to photograph the prominences projected against the disk as dark flocculi. They are generally dark because the hydrogen or calcium gas is comparatively cool at high levels, and thus absorbs the light from the hotter region below. The same plates also show the bright (hotter) gases at lower levels.

In 1908 the Sun's disk was first photographed at Mount Wilson with the red hydrogen line $H\alpha$, and great vortices or cyclonic storms were discovered

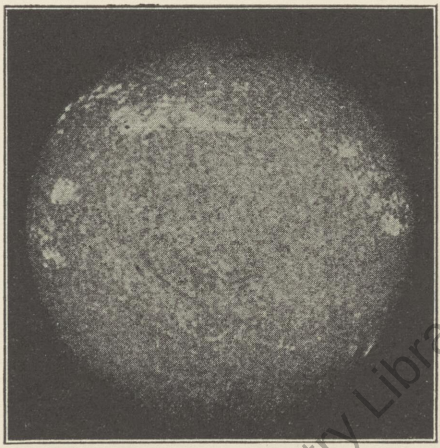

FIGURE 5

The calcium flocculi, photographed with the calcium line K, September 27, 1926. (Compare with Figure 4.)

in the upper hydrogen atmosphere. These were found to center over sun-spots, and soon led to the detection with the spectroscope of strong magnetic fields in all spots.

This brief reference to the photographic registration of the chief phenomena of the solar atmosphere is necessary to a comprehension of the new work of the spectroheliosope. The reader who is interested in the details should consult the original papers and also the many publications of Deslandres, Evershed, St. John, and others who have made many discoveries and important contributions in this field of research.*

* Most of these papers may be found in the journals *Astronomy and Astrophysics, Astrophysical Journal, Comptes Rendus* of the Paris Academy of Sciences, *Monthly Notices* of the Royal Astronomical Society, and in the Publications of the Meudon, Kodaikanal, Yerkes, and Mount Wilson Observatories.

Our daily series of photographs of the solar atmosphere, begun at the Kenwood Observatory in 1891 and continued later at the Yerkes and Mount Wilson Observatories, contains many thousands of plates of the prominences and flocculi. Familiarity with these results has served to enhance my enthusiasm for the new possibilities recently opened by the spectrohelioscope.

New Opportunities for the Amateur

The spectroheliograph, as already stated, builds up its monochromatic image gradually, slit-width by slit-width, as the slit moves slowly across the

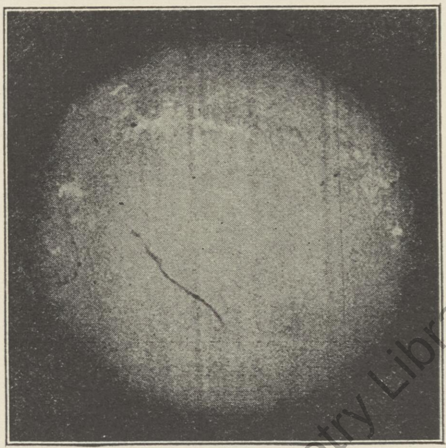

Figure 6

The hydrogen flocculi, photographed with the red hydrogen H a, September 27, 1926. (Compare with Figures 4 and 5, taken nearly simultaneously.)

Sun. The photographic plate, as it were, thus "sees" at any instant only a narrow strip across the solar image two or three thousandths of an inch wide, which it faithfully records, in its varied intensity, as an element in a composite image. A different mechanical arrangement permits the same idea to be employed in revealing a large area of the hydrogen atmosphere directly to the eye. It is only necessary to utilize the well-known principle of the persistence of vision.

The first slit of the spectroscope, on which the Sun's image is formed, and the second slit, on which the red hydrogen line falls, are so connected that when the first slit moves, the second slit also moves in such a direction and at such a rate as to remain exactly upon the displaced hydrogen line. Then,

if the slits are rapidly oscillated to and fro across a portion of the solar image, this region will be seen in hydrogen light through an eyepiece focused on the second slit.

It is astonishing how this simple method, which was tried (but discarded) by Young in 1870 for observing the prominences at the limb, seems suddenly to bring to life the flocculi on the disk, which appear fixed and inert on photographic plates. There are several reasons for this. As the photographer

FIGURE 7

Bright and dark hydrogen flocculi, photographed with the red hydrogen line H α, September 9, 1915. (Mount Wilson.)

using a spectroheliograph cannot see what is happening, he makes his exposures in a routine way and thus almost invariably fails to catch the successive phases of remarkable short-lived phenomena that often afford marvelous spectacles to the visual observer, who can pick out at a glance the most interesting and most active regions. Thus I have repeatedly seen with the spectrohelioscope the swift flow toward sun-spots of masses of hydrogen larger

than the Earth, adequately recorded only once with the spectroheliograph in a period of twenty years.

But the spectrohelioscope has another more important advantage, which permits the observer instantly to interpret phenomena missed altogether by the spectroheliograph, or so incompletely recorded that their interpretation remains obscure. This is due to the use of the "line-shifter", an adjustable plate of plane-parallel glass behind the oscillating second-slit, which permits the observer to set any part of the red hydrogen line or its

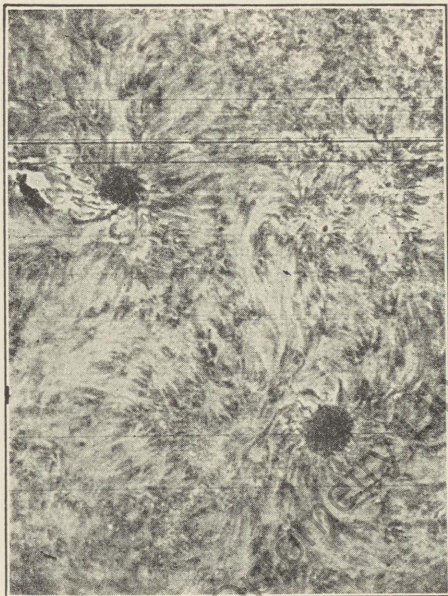

FIGURE 8

Counter clockwise (N) and clockwise (S) hydrogen whirls associated with sun-spots in the northern and southern hemispheres of the Sun, September 9, 1908. (Mount Wilson.)

wings on the slit during observation. In this way he can observe the form of the flocculus given by any part of the line, which is greatly distorted to the violet or red if the hydrogen is moving with high velocity toward or away from the Earth.

Lockyer and Young long ago saw and described the strange "motion forms" thus produced (Figure 10). The bulge of the C (now called $H\alpha$) line toward the violet observed by Young on August 5, 1872, meant that the

hydrogen gas at a point near an active sun-spot was approaching the Earth at a velocity of about 120 miles per second. Thus if a series of photographs of the $H\alpha$ line is made, with the spectrograph slit stationary at many successive sections across such an eruption, the measured displacements of the line will give the radial velocity at the corresponding positions of the slit. This is the principle of Deslandres's "velocity spectrograph".

The spectrohelioscope is far quicker in action and its results are instantly interpreted. Imagine an arch of hydrogen, representing the trajectory of masses of gas continually shooting along the same path near the middle of the Sun. Like a projectile, the gas moves rapidly upward, curves over and travels nearly parallel to the surface, and then falls, curving back toward the

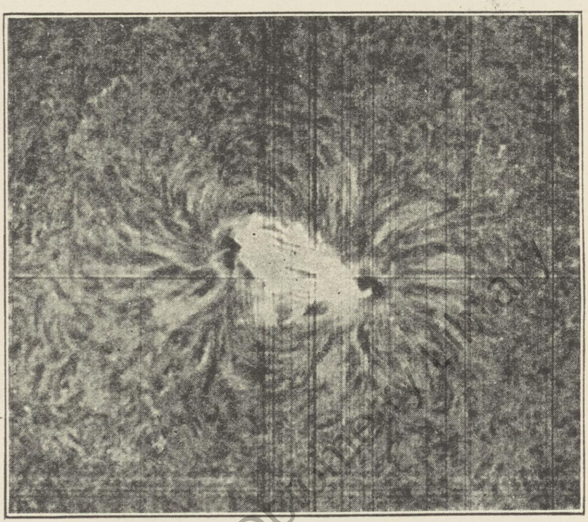

FIGURE 9

Complex hydrogen whirls associated with a large bipolar sun-spot, August 29, 1924. (Mount Wilson.)

surface. Thus in the spectroscope the $H\alpha$ line would appear twisted toward the violet at the point of eruption, less and less displaced nearing the center of the arch (where the velocity in the direction of the Earth becomes zero), and increasingly displaced toward the red as the descending branch of the arch is approached. As the projection of such an arch against the surface usually appears curved, and as its form cannot be seen at all without a spectrohelioscope, the task of photographing the $H\alpha$ line at several points along the arch, measuring its distortions at all these points on the photographs and interpreting the results would naturally take considerable time. Mean-

while the phenomenon may have passed through several stages and perhaps ceased altogether.

With the spectroheliosope the whole analysis can often be completed in a few seconds. As the $H\ a$ line is moved across the oscillating slit the darkest spot (maximum of intensity) of the arch is seen to move from its origin at the point of eruption (violet side of $H\ a$) toward the center of the arch (center of $H\ a$) and thence to the point of fall (red side of $H\ a$). By reading the divided circle of the line-shifter at these points the corresponding radial velocities are obtained at once. Perhaps the most beautiful application of this method is in the measurement of the flow of hydrogen into the vortices centering in sun-spots.

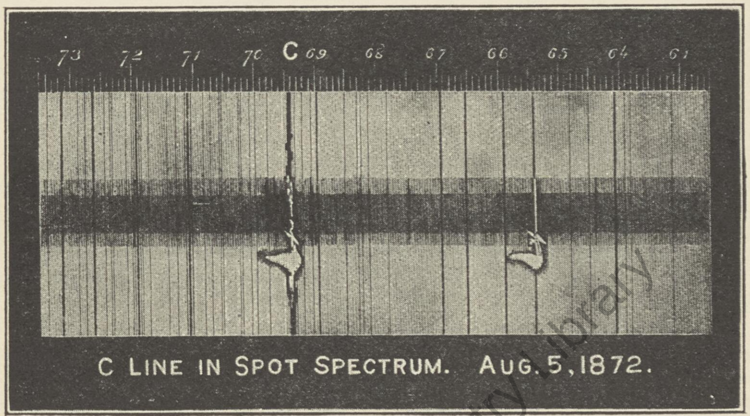

FIGURE 10

Red hydrogen (C or $H\ a$) in sun-spot spectrum, as observed by Young on August 5, 1872. The distortion is due to motion of the hydrogen in the line of sight of about 120 miles per second. (From Young, "The Sun," 1884.)

CHAPTER II.

A Simple Solar Telescope and Spectrohelioscope

As explained in the last chapter, some of the most spectacular and beautiful phenomena in the heavens are visible daily in the solar atmosphere. These have so recently become accessible to visual observation that they are but little known, and thus offer promising opportunities for discovery to amateur astronomers. The purpose of this chapter is to explain the construction of the simple instruments necessary to observe them.

Solar Telescope

The telescope required is of the coelostat type, giving a fixed solar image 2 inches in diameter for study with a spectrohelioscope (Figure 11).

The coelostat consists of a plane mirror* of plate glass, 5½ inches in diameter and ½ inch thick, mounted with its surface parallel to the Earth's axis and uniformly rotated by an ordinary (two dollar) clock movement at the rate of one complete revolution in 48 hours.

The parallel rays of sunlight reflected from the silvered front surface of the coelostat mirror fall on a second mirror of plate glass, 4½ inches in diameter and ½ inch thick, mounted in a fork, and provided with slow-motion screws controlled by the observer with rods or cords. This mirror is fixed during observation, but the slow motions permit the observer to move it sufficiently to bring any point on the Sun's disk or circumference to the center of the slit of the spectrohelioscope.

These two mirrors, of course, do not form an image of the Sun. They serve merely to send the parallel rays in a chosen direction (usually north) and to hold them there during observation. The solar image is formed by a single plano-convex lens 3 or 4 inches in diameter and of 18 feet focal length, mounted on a support which can be moved north or south with a coarse screw by the observer for focusing the image on the slit. Such a lens is suitable only for observations with monochromatic light. An achromatic lens is needed for direct observations of sun-spots in white light.†

The coelostat, second mirror, and lens are shown in Figure 12, mounted on a wooden tripod south of a small garage containing the spectrohelioscope. For permanent use a brick or concrete pier, covered with a small wooden house easily removable when observations are to be made, should be erected as a more stable base. The coelostat may stand either east or west of the second mirror support (out of its shadow), but on account of the varying

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* The front surfaces of the coelostat and second mirrors should be plane to about one-quarter of a wavelength.

† A small telescope having an achromatic lens one or two inches in diameter, with eyepiece permitting a solar image from four to six inches in diameter to be projected upon a white card for recording the positions of sun-spots, will serve as a useful auxiliary. The larger spots can be fairly well seen, however, on the 2-inch image given by the single lens, especially if it is looked at on a white card through dark spectacles supplemented by a piece of red glass.

altitude of the Sun, it must be moved north or south and fixed for any given date at a point where the reflected beam falls on the center of the second mirror. The beam is then maintained in place by the driving clock.

The Spectrohelioscope*

The spectrohelioscope is merely a long-focus spectroscope, provided with a pair of rapidly oscillating slits affording a view of a portion of the Sun's

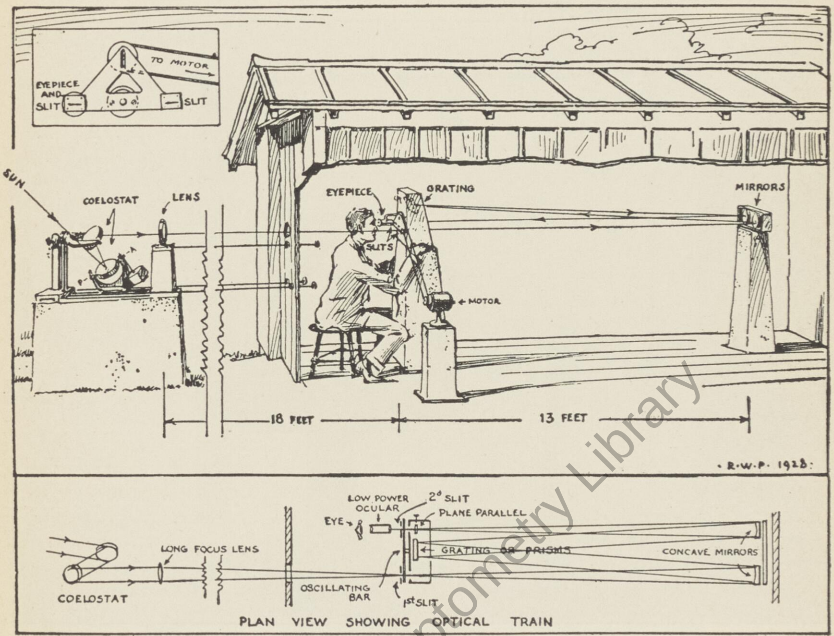

Figure 11

Perspective and plan of solar telescope and spectrohelioscope, showing path of the rays used in forming a red (H a) hydrogen image of a part of the solar atmosphere. Drawing by Russell W. Porter.

atmosphere in the monochromatic light of the red hydrogen line known as *H a*. It gives such an image of the Sun as might be obtained through a red screen (if such could be made), transmitting no light except that due to this hydrogen line.

* See the following papers by the writer: "The Spectrohelioscope," *Proceedings of the National Academy of Sciences, 10*, 361, 1924; "The Spectrohelioscope," *Publications of the Astronomical Society of the Pacific, 38*, 96, 1926; "Some New Possibilities in Solar Research," *Nature*, July 3, 1926; "The Fields of Force in the Atmosphere of the Sun," *Nature*, May 14, 1927.

An ordinary spectroscope consists of a narrow slit, a (collimating) lens for making the divergent rays from the slit parallel, a grating (or one or more prisms), and a second lens for forming an image of the spectrum, which is examined by the observer with an eyepiece. The grating is a plane surface of polished speculum metal, on which about 15,000 lines per inch are ruled with a diamond. This diffracts the incident light, and produces a number of spectra resembling those given by prisms.

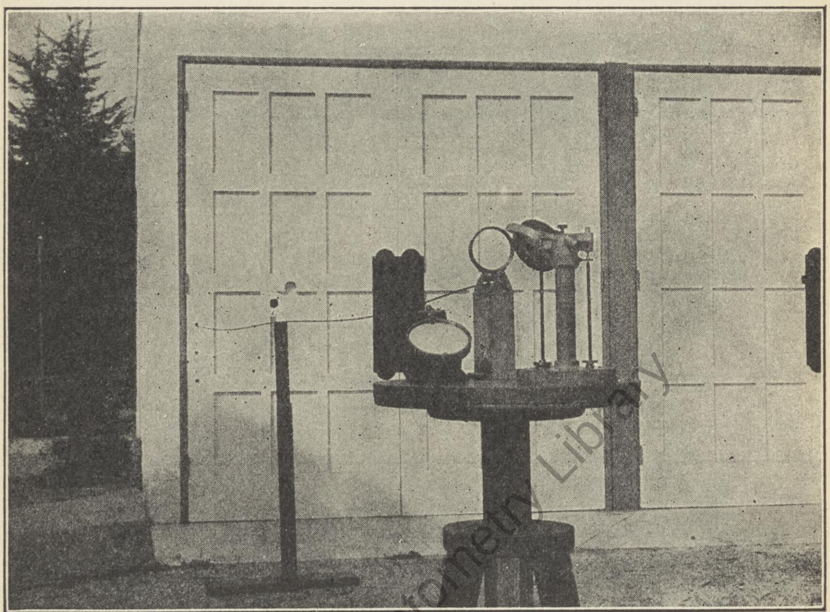

FIGURE 12

The small solar telescope employed in the experiments at Pasadena. The coelostat mirror at the left, driven by clockwork, reflects the sunlight to the second mirror which is provided with slow-motion screws for directing the solar image. This is formed by the simple lens (center), adjustable by a screw for focusing the image on the slit of the spectroheliosope 18 feet away, within the building.

In the present instrument two spherical concave mirrors, of 2 inches aperture and 13 feet focal length, mounted upon a single support permitting them to be focused by a screw, are used in place of lenses. Light from the solar image falls upon the collimating mirror 13 feet away, and is returned (by a slight inclination of the mirror) to the grating or prisms mounted behind and above the slits. The red ($H\,a$) region of the spectrum thus formed, falling upon the second concave mirror, is reflected to a sharp focus at a point near

the first slit. Here it falls upon a second slit, adjusted so as to coincide with the center of the *H a* line. (See bottom diagram in Figure 11.)

The operation of the instrument will now be evident. If the first slit, on which the solar image is focused, is moved in the plane of dispersion, the spectrum will move a corresponding distance. To remain on the line, the second slit must be displaced accordingly. The first and second slits are therefore carried at the opposite ends of a very light metallic bar, mounted on a bearing halfway between them. This bar is oscillated rapidly by a small electric motor, through an amplitude (usually about a quarter of an inch) which is limited by the brightness of the spectrum. The observer, looking through the oscillating second slit, which remains exactly on the *H a* line, sees by persistence of vision a hydrogen image of a portion of the Sun. This may

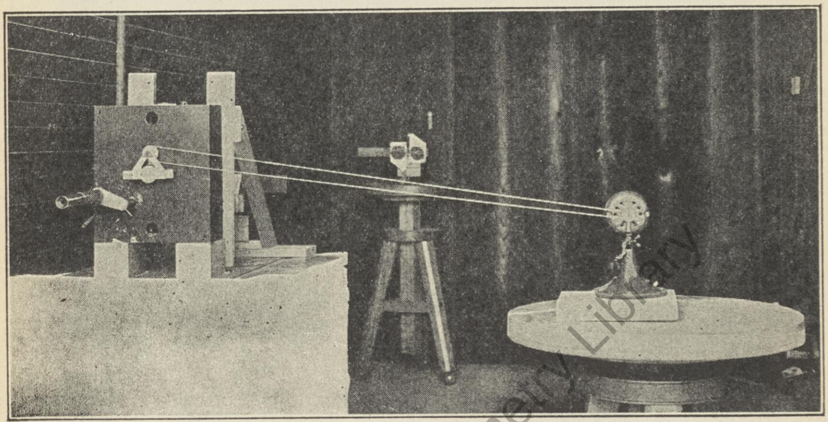

FIGURE 13

Simplest form of spectroheliоscope, of 13 feet focal length. Sunlight passing through the first slit (right) falls on the collimating mirror, which returns a parallel beam to the grating mounted above the slits, behind the casting. An image of the H a line of hydrogen in the first order spectrum is formed by the left concave mirror on the second slit. When the slits are rapidly oscillated by the mirror, a portion of the solar atmosphere is seen in hydrogen light through the eyepiece on the left (here turned aside to show the second slit).

include a part of the limb, where a prominence appears bright against the sky, and at the same time a part of the disk, upon which a portion of the same prominence may extend as a dark flocculus.

High velocities in the line of sight produce distortions of the *H a* line, toward the violet when the gas is approaching, toward the red when it is receding. To see a mass of hydrogen receding at a velocity of, say, sixty kilometers a second the second slit must be set, not on the normal position of the *H a* line, but at a position completely outside of it toward the red. A simple "line-shifter" is employed for this purpose. A graduated arc indicates

the displacement of the line from the zero position, and thus gives the radial velocity of the portion of the flocculus under observation.

In the above design the slits are only $3\frac{1}{2}$ inches apart. They are therefore mounted horizontally, so as to permit direct observation through the second slit by the right eye without obstruction of the solar image on the first slit by the observer's head. The bar that carries them, like the slits themselves, is extremely light and stiff. An upward extension of this bar is pierced by a fibre-lined vertical groove, in which a steel pin, fixed eccentrically in the head of a horizontal shaft, serves as the driving device. A small electric motor,

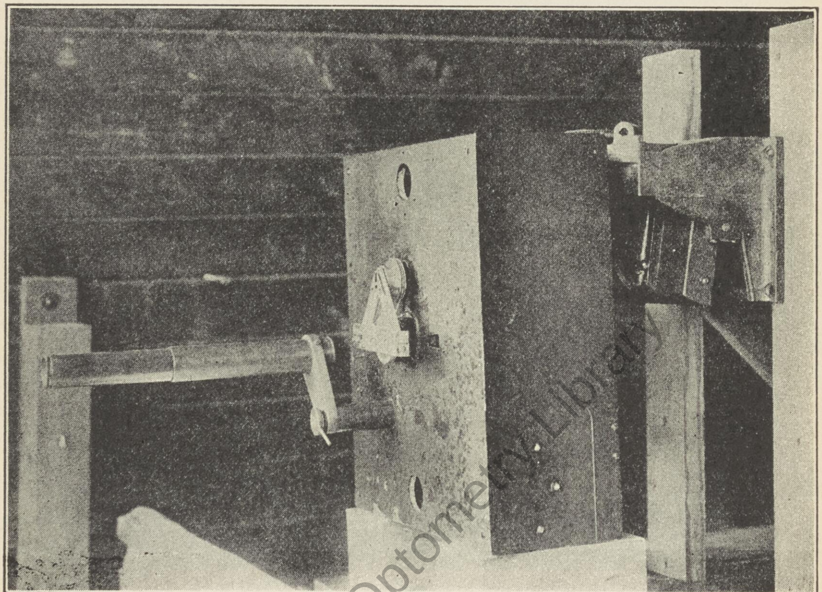

FIGURE 14

The oscillating slits, eyepiece, and grating holder, on temporary wooden supports.

belted to a pulley on this shaft, causes the slits to make thirty or forty single oscillations per second. The amplitude is about a quarter of an inch or less, and the motion is smooth and quiet, though there is a slight flicker unless a higher speed is used, which is likely to cause vibration of the grating, unless this is very firmly mounted on an independent support. However, a little flicker does no harm, and is soon forgotten by the observer.

The second slit is viewed through a positive eyepiece magnifying from two to four diameters. The line-shifter, a strip of plane parallel glass, is mounted behind the second slit on a short shaft, provided with a large milled head for

easy rotation by the observer and a divided arc showing the displacement in angstroms or the equivalent radial velocity. An important adjunct is a screen to prevent the diffuse light of the collimating mirror from reaching the eye of the observer.

Similar protection against the glare of the bright solar image on the first slit should be provided, and a tube large enough to prevent reflections from its inner walls should extend from the slit to the opening through which the sunlight enters the building. In fact, the observing room should be as dark as possible.

I have found by experiment that with slits 0.004 inch wide, oscillating with an amplitude of $\frac{3}{16}$ inch, the bright and dark hydrogen flocculi can be well

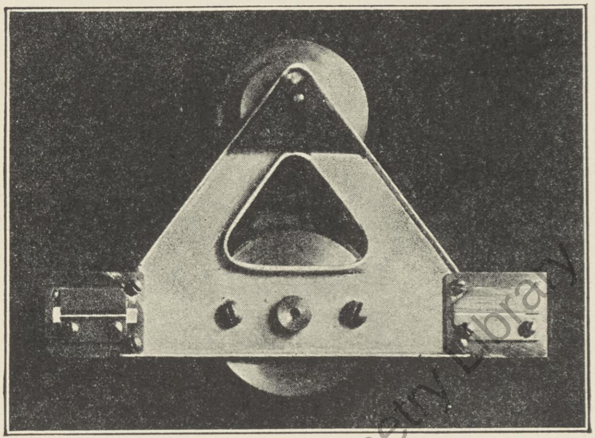

FIGURE 15.

The oscillating slits. In this simple design the slit jaws are fixed in position at a width of three or four thousandths of an inch. The rectangular openings at the ends of the second (left) slit permit the H α line to be seen for adjustments when the slits are at rest.

seen on the Sun's disk when the grating aperture is reduced to $1\frac{3}{16} \times 2$ inches.* A larger grating naturally gives a brighter image, in which more detail can be seen, but the above will serve for most classes of work.

Suitable gratings, even of the smaller size just mentioned as a minimum, may not be obtainable. I have therefore tried a less expensive arrangement, which may be adopted by amateurs who wish to build their own instrument and are content (until a good grating or reflecting replica can be obtained) to see only the more conspicuous phenomena. This is a pair of 60° prisms,

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* This is nearly the size of Hilger's plane grating K14, ruled with about 14,400 lines per inch at the National Physical Laboratory on a surface 3.5 x 5 cm.

which should be of very dense flint, and may be only just large enough to transmit a beam 1 inch in diameter, though a somewhat larger aperture is preferable. The dispersion of two ordinary flint prisms (here made equivalent to four by the use of a small plane mirror, which returns the light through the prisms to the second concave mirror) is less in the red than that of the first order of a (15,000) grating, and their performance is much inferior to that of a good grating; but with suitable slit-widths they will show the stronger bright and dark flocculi, as well as the prominences at the limb. If, as I greatly hope, a satisfactory method of producing cheap reflecting grating replicas of excellent definition can be found, these may ultimately become available in place of original gratings or prisms.*

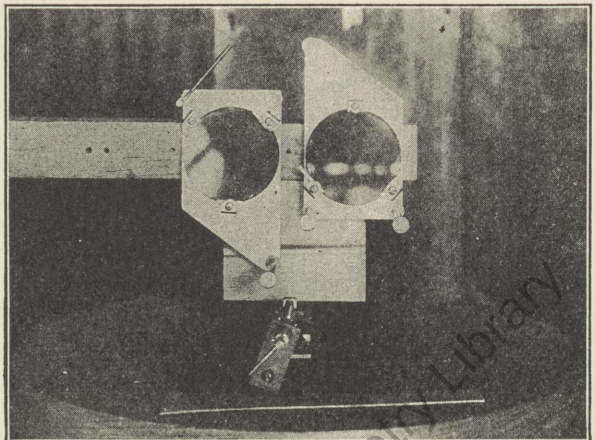


FIGURE 16

The two spherical concave mirrors of 13 feet focal length. In the finished design the left mirror is provided with a finer adjustment, to tip the mirror and thus move the H a line along the second slit to the position where it exactly follows it when in motion.

A better design for oscillating slits has recently been developed by my instrument maker, Mr. Hitchcock. In this form the slits are vertical and farther apart, and the driving mechanism is improved.

As in the case of the spectroheliograph, a monochromatic image can be produced either by motion of narrow slits with respect to the solar image, or

* The most promising means of reproducing reflecting gratings appear to be either an electrolytic process or the method described by Merfield (*Proc. Roy. Soc. Victoria*, vol. 38, 1926). The latter can perhaps be used for copying speculum metal as well as glass gratings by adopting means of preventing firm adhesion of the cathode deposit. The difficulty thus far experienced with the electrolytic method is not in securing good reproductions of the rulings, which are beautifully copied, but in obtaining replicas with plane surfaces. Those made for us have been warped several waves.

by motion of the solar image with respect to the slits. The chief difference between the two instruments lies in the fact that the spectroheliograph builds up its image gradually, slit-width by slit-width, by a slow motion of the slits or of the solar image with respect to the photographic plate, while the spectrohelioscope must reveal a considerable area of the image at once to the eye, which obviously could not see the forms of the flocculi through slowly moving slits a few thousandths of an inch wide. Hence the rapid motion of the slits or of the solar image required for the spectrohelioscope.

I have tried successfully oscillating bars carrying from one to five slits at each end and a rotating disk carrying fifty radial slits. The most effective

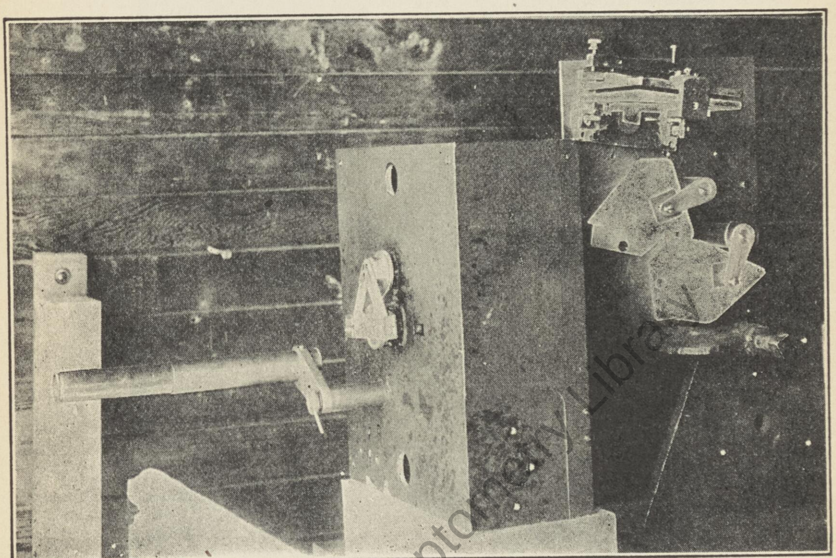


FIGURE 17

Two dense flint glass prisms and a plane mirror to double their dispersion, which can be used if no suitable grating can be obtained.

means I have tested of producing rapid motion of a portion of the solar image with respect to fixed slits is a square prism of glass mounted before each of the slits, rotating uniformly about an axis parallel to them. The portion of the solar image under observation reaches the first slit through one prism, while the resulting fixed monochromatic image is seen in an eyepiece focused through the other prism on the second slit. This ingenious device is due to Dr. J. A. Anderson. It is somewhat more expensive than the oscillating slits, and seems to show no details of the flocculi not visible with them. However, the elegance of this method, and the complete freedom from vibration and

flicker which it affords, make it an attractive alternative for oscillating slits. It can be readily attached to any Littrow spectroscope of suitable dispersion, but I have found this type of spectroscope (in which a single lens serves for both collimator and telescope) much less satisfactory for the purposes of the spectroheliosc ope than the two-mirror form illustrated, because of the impossibility of excluding from the eye the light due to the illumination of the collimating lens and the grating behind it by the sunlight from the first slit. The reflected light can be excluded by using a suitable lens for the collimator, but the remaining diffuse light, superposed upon the *H α* line, materially reduces the contrast of the flocculi, even when a suitable red glass is placed over the eyepiece.

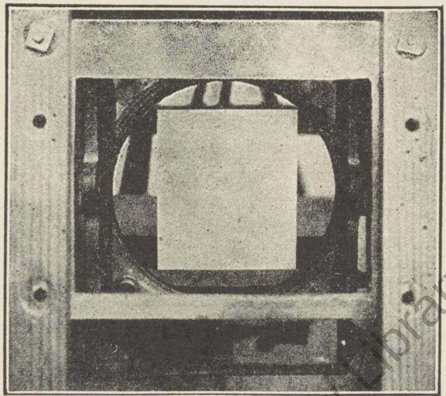


FIGURE 18

Grating seen from the north, above windows in casting corresponding to first and second slits. The plane-parallel glass plate of the line-shifter is seen from the right (second) slit. (The line-shifter, which is unnecessarily long for this instrument, was borrowed from the larger, vertical spectroheliosc ope of the Solar Laboratory, described in the Scientific American, March, 1927, page 186.)

The spectroheliosc ope shown in the illustrations was built from various parts that happened to be available, and does not represent the final design. The working drawings now in preparation will show a more compact support for the two concave mirrors, and various other improvements. Blueprints of these drawings, detailing all the parts of the various instruments mentioned in this paper, may soon be obtained at low cost by writing to the Mount Wilson Observatory. It should be stated whether blueprints are wanted of (A) the least expensive form of spectroheliosc ope (shown in Figure 13); a more expensive form (B), with vertical adjustable slits and improved oscillating bar; or a similar design (C), provided with Anderson's rotating prisms.

In the space here available I have been unable to give many important details regarding the construction, adjustment, and use of the instruments. I hope to describe these later, partly in the *Publications of the Astronomical Society of the Pacific* and more completely in a small book on solar research for amateurs. Let me add that all those interested should read such books as Lockyer's *Contributions to Solar Physics,* Young's *The Sun,* and Abbot's *The Sun,* the latest of which is nearly up to date. Lockyer's book, published

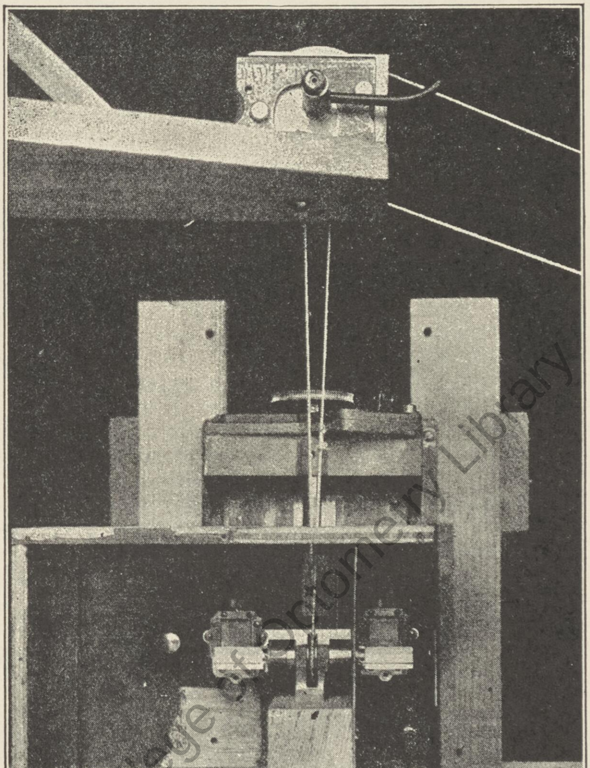


FIGURE 19

Anderson's rotating prism device for use with fixed slits. A square prism of glass rotating uniformly causes a succession of images of the Sun to move across the first slit at the rate of four per revolution. When the second slit (set on H a) is viewed through a similar prism rotating at the same rate, a stationary image is seen in hydrogen light.

by Macmillan in 1874, contains a fascinating account of the early solar spectroscopic work and the first observations of the prominences. I have referred briefly to some of this early work in an article called "Exploring the Solar Atmosphere", published in *Scribner's Magazine* for July, 1928.

A coelostat (in which the plane of the mirror is parallel to the polar axis) is recommended in this article instead of a heliostat, chiefly because it gives a solar image which does not rotate during observation. The rotation of the image obtained with a heliostat is slow, however, and the only difficulty it involves in visual observations is the necessity of redetermining the orientation from time to time, in case the heliographic positions of the prominences or flocculi are to be recorded. The simplest possible substitute for a coelostat or two-mirror heliostat is a polar heliostat, which is merely a polar axis carrying within a fork a single mirror, which sends the sunlight upward or downward through a lens toward the north or south pole. In this case (unless a second mirror is used) the spectrohelioscope must be mounted in a plane parallel to the Earth's axis.

Part X.

Miscellany

By Albert G. Ingalls
Associate Editor, Scientific American

It would be remarkable, indeed, if the beginner did not occasionally "strike a snag." Sometimes troubles arise over little points which seem obvious to the expert. The following chapter, then, is a miscellaneous collection of odds and ends, some of which it is hoped will prove useful.

What is meant by a one-third stroke? Answer: When the upper disk overhangs the lower by (roughly) one-sixth of its diameter at either end of the stroke. Thus, for a six-inch mirror, come at each end to an overhang of about an inch—not two inches. But in rough grinding, as Ellison says (Part II, Chap. II), the stroke may be much longer. Too long a stroke will probably hyperbolize the mirror.

Why can I not seem to avoid getting scratches on my mirror during fine grinding? Answer: Perhaps you have mixed a little coarse carborundum with finer sizes. Don't run your finger into a coarse size before a fine size. If necessary to do this, do it afterwards. Keep the can closed when not in use, and put it away upside down, thus keeping dust and grit out of the crack around its cover. Tack a few newspapers on the ceiling over your work, otherwise, people walking about upstairs will keep jarring down grit from the joists above you. Again, you may have previously wiped coarse carborundum on your working clothes and transferred it to your mirror several days later, during the finer stages of grinding. It is better to keep finer sizes—and rough also—in a clean wooden box, turned on its side. This keeps out the falling grit. It is a great temptation while polishing to watch the surface of the mirror from time to time. Whenever this is done, do not *rub* the surface dry, for this is a fruitful source of scratches; *blot* the surface with cloth or paper towel.

Scratches on the mirror do very little actual harm, since they cut off only a small fraction of the light, but they make the job look mussy. You will be more proud of your workmanship if your mirror is free from them. To insure this, one must be very painstaking, often to the point of seeming fussiness.

Prisms are preferable to silvered flats for small telescopes for they have no silvered surface to care for and renew. "For those who nevertheless wish to make a diagonal, the easiest way," writes R. W. Porter, "is to select a fairly flat piece of commercial plate glass. A piece of broken windshield, picked up at a repair garage, will do. Slight departures from an optically flat surface are relatively unimportant so near the focus. Another way is to figure the surface by fine grinding three small disks of glass on each other—1 on 2, 2 on 3, 3 on 1, etc.—and then polishing each disk separately. Test them by noting the interference fringes produced by pressing two of

the surfaces together. If the fringes are straight, the surfaces are flat; if they are curved, the surfaces are either convex or concave. In order to see these fringes, view the surfaces in a dark room, under the flame of an alcohol lamp, on which ordinary table salt has been sprinkled, or throw a pinch of salt on the burner of a gas stove. If all three disks, tried in all three combinations, show straight fringes, they are all flat. If they show one of Newton's rings, they are curved 1/100,000 of an inch; if two rings, 1/50,000 of an inch. The faces of one's prisms may also be tested for flatness in this manner, by laying the prism on one of these glass flats and observing the fringes. To test the right-angle, hold the prism in front of your eye, about a foot away, with the hypothenuse side facing you. Observe the reflection of the pupil of your eye. If the angle of the prism is just 90°, it will be perfectly round. If it is not 90°, the pupil will be elongated or the reverse, depending on whether the angle is greater or less than 90°."

How can I tell when the fine grinding is finished? Answer: Whittle a wedge, three inches long and ⅝ inch thick. Lay it on the mirror, hold the latter in line between the eye and an electric light placed a foot or two farther away. Then slowly lower the mirror, keeping it horizontal. If the red image of the filament remains visible on the mirror until you can sight down the slant of the wedge (that is, at about a 12-degree angle), you can begin polishing—provided no larger pits than the average size remain.

Is it worth while to finish fine grinding with emery? Answer: The writer finds it decidedly so. The polishing is done in much less time than the rules called for. Emery, like carborundum, makes pits, but they are shallower. The emery is used exactly as the carborundum is used. Every minute's work with emery pays fine dividends in time saved during polishing, later on.

Why is my pitch lap all speckled over with little bubble holes? Answer: The pitch was probably boiled and the bubbles that arose from the bottom did not escape from it. Do not heat it so fast.

Is pitch very inflammable? Answer: Take a match and try a small piece. During the melting of pitch, it is well to have a pot cover handy, to clap on in case of fire.

For the first few minutes after I begin my daily polishing, the pitch lap acts as if possessed of pure cussedness, gripping the mirror suddenly and letting go unexpectedly. No two strokes are alike, nor are they even. Answer: Have you cold pressed the lap, as explained in Part II, Chap. IV? If so, and if the "acting up" persists after a few strokes, stop and cold-press again. Pitch laps usually act this way at first while still cool, even if they are made right. They may soon settle down to business, if the pitch is not too hard. In all cases, however, the "bad acting" may indicate poor contact. This is a point about which it is hard to be definite. Whatever you do, avoid haste, and think the matter out. In cold pressing, use 10 or 15 pounds weight.

"Keeping good contact is the secret of avoiding zones," Mr. Porter adds to the above. "Whenever the glass is removed from the lap, evaporation

takes place, lowering the temperature of the lap and altering its shape. Moral: Have patience to polish for long intervals, and *always* cold press after exposing the lap. I have often safely left my glass on the lap, between polishings, for a day or so, simply by swathing it in wet compresses and covering with an inverted pan to retard evaporation, watching it from time to time to see that the rags do not go dry. After these intervals, the glass is always found in perfect contact, giving the operator by the feel of the stroke a sense of assurance that every part of the lap is doing its work."

How shall I get the handle off the mirror without danger of breaking it? Answer: Pitch is quite strong except under sudden shock. Hit the handle a smart, sidewise rap with the screw driver handle. It will fly off without danger of breaking the speculum. The back of the glass may then be scraped and cleaned with turpentine.

What if I drop my mirror and break it? Answer: Get another glass disk. One is enough. Turn the tool over, beginning again with the flat side, and place it on a ring of pasteboard, in order to insure steadiness. Your second job will go ahead altogether faster than the first one, thus giving you so much assurance that you will be almost glad you broke the first. This, at least, was the writer's experience with his first speculum, and it will also be the case if you make more than one telescope.

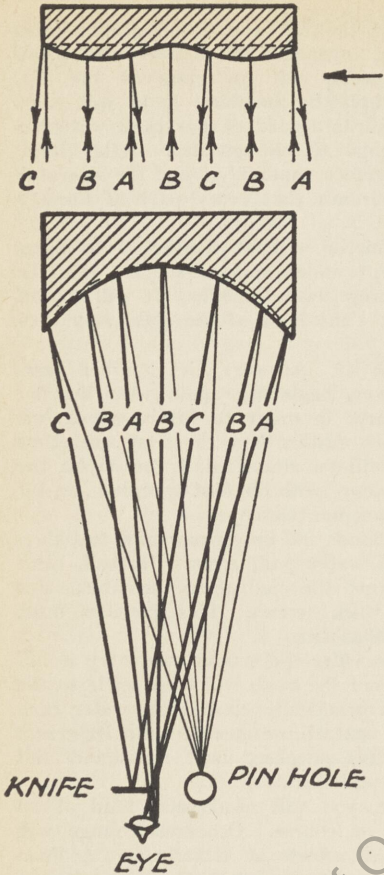
To keep well-meaning, but damaging, hands off the mirror and tool during your absence, buy a cheap galvanized water pail, remove its bail, bend the two "ears" out at right angles, invert the pail over the work, and "lock" it down by means of two short, thick screws. This excludes dust, as well as children and house-cleaning enthusiasts.

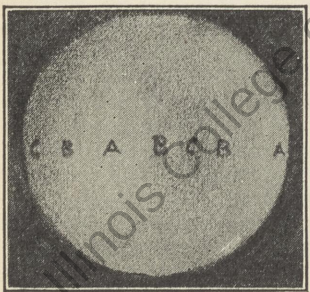
Instead of a shallow basin in which to rinse the cotton swab, try a tall container of some kind. The grit freed from the swab will then settle to the bottom, where it will stay. Thus you get practically clean rinse water each time. For example, the writer used the central container of the ice-cream freezer, which is admirably shaped for this purpose, until found out and reprimanded! A clean, tall crock is also excellent.

When you begin polishing with rouge, you will need some kind of an "all-over" garment, covering the sleeves, of course. Otherwise, rouge will stain your clothing in spite of any and all efforts at cleanliness. A linen duster is excellent. It is well, however, not to wear it during the grinding with carborundum—unless it is washed before the polishing begins. This is because grit may be easily transferred to a finely polished surface by means of the clothing.

An electric lamp will not suffice for the shadow test because the pinhole acts as a lens (like a pinhole camera) and you will simply get an inverted image of the filament thrown on your mirror, giving uneven lighting. Speculum makers have wasted many hours trying to adapt the electric light to this work, trying all sorts of dodges without success.

In pouring melted pitch on the tool, wrap a wetted strip of paper twice around it for a temporary retaining wall, fastening the ends with a daub





THE PARABOLOIDAL SHADOW

The accompanying illustration may explain the peculiar distribution of lights and shadows that is characteristic of a paraboloidal mirror with the knife-edge at its mean center of curvature (when the lights and shadows on either half of the mirror balance in respective areas). Under these conditions the mirror has the appearance of being illuminated from the side (see arrow), and of having a ring-like bulge. At bottom is a shadow of this sort, with letters corresponding to those of the apparent cross-section at top. In testing a spheroidal mirror we saw that the reflected rays all converged as radii to the eye and made the concave disk look flat. Such a spherical curve is dotted in behind the parabola in the central figure. The parabola touches this curve at only three places. In between, and between the curves, are two narrow strips and it is to the effect produced by these strips that we can credit our shadows. As the concavity of the mirror is actually very slight, we shall straighten out these strips and then their analogy with the bulge of the top figure will be obvious. Thin as they are on the mirror itself, these strips alter the direction of the reflected rays by a few thousandths of an inch along the axis of the mirror, and thus they may be thought of as long "pointers." For example, at eight feet the minute changes in curvature are multiplied, in effect, many times. Therefore, rays A, A, enter the eye, and the areas from which they are reflected are bright. Rays marked C are swung slightly to the left, striking the knife-edge, hence, their areas are dark. But rays marked B, graze the knife-edge and the areas from which they are reflected appear gray. In practice we make use of this parabolic shadow only in order to make sure that the curve is an evenly flowing one, for the amount of parabolizing is determined by diaphragming out all but the center and margin, as explained by Ellison and Porter.

of hot pitch (string is unnecessary). While it is still damp, and after the pitch has partly "set," strip it off.

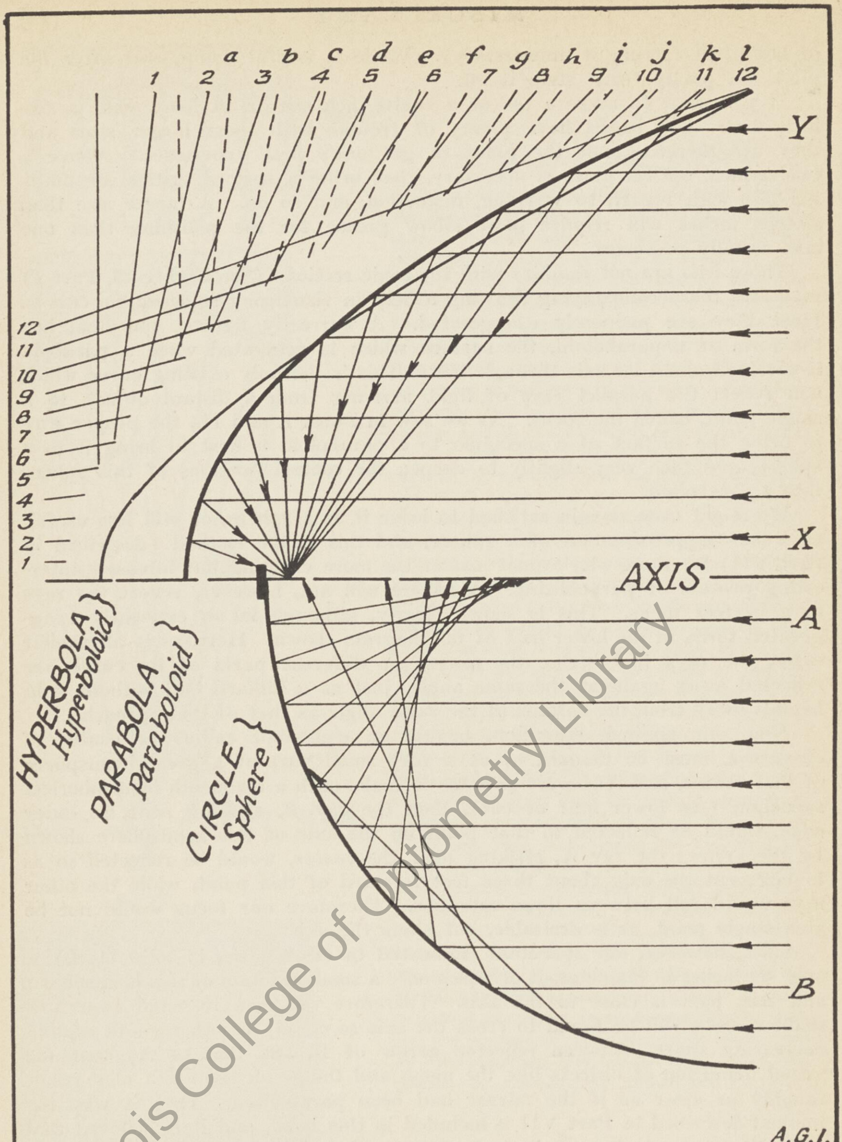
If you want to make a ten or a twelve-inch mirror, at least make a six-inch first. Old hands have plenty of trouble with these larger sizes and they are therefore not the place to get one's first experience. Above a twelve-inch, optical glass is necessary, that being a sort of critical or limiting size with regard to warping, distortion, and so on. A larger size than sixteen inches will require more elbow grease for the polishing than one man usually possesses.

Those who are not familiar with the conic sections (See Figure 15, Part I) may find the accompanying drawing a help in visualizing some of the curves. Here they are purposely exaggerated. A correctly figured speculum has the form of a paraboloid, the surface which is generated when a parabola is revolved about its axis through 360°. This is the only existing curve which will reflect the parallel rays of light arriving from a distant object, to a single point, called the focus. As we saw in Parts I. and II., the proper way to bring the surface of a speculum to a paraboloid is first to bring it to a sphere, and then very slightly to deepen the central portions of this sphere into a paraboloid.

We might even remain satisfied to leave it as a sphere, or still less useful, as a mere approximation of a sphere, and this is the method (described in Part VII) for those who cannot master the more exacting but intensely interesting process of parabolizing. A sphere will not, however, reflect the rays to a perfect focus. This is shown clearly, although in an extremely exaggerated form, in the lower half of the diagram shown. Here, as in all similar cases, the rays that strike the mirror at different parts of its curve are reflected away again at the same angle, just as a billiard ball without spin bounds away from the cushion at the same angle as that of its approach.

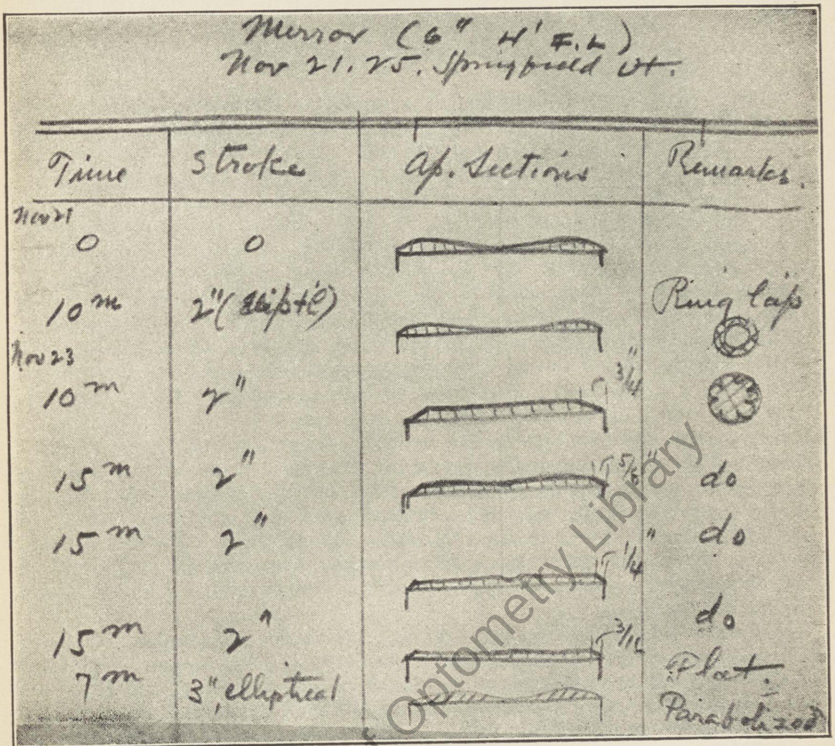
Now our six-inch speculum, having an eight-foot radius or center of curvature, must be thought of as a very small part of a great hemisphere of that radius, and if it were possible to make such a mammoth hemispherical speculum (see lower half of cut), then the ray B, striking near its outer *edge,* would be reflected to that point on the axis of this hemisphere shown by the arrow; the ray A, striking near the *center,* would be reflected so as to intercept the axis about three feet forward of this point, while the other rays would fall between these extremes. Therefore our focus would not be at a single point, as is desirable, but along the axis.

Since, however, our speculum (indicated to exact scale, in solid black) is only six inches in diameter, it occupies only a small fraction of this hemisphere, and that part is close to the axis. Therefore the rays reflected from this shallow curve will be found to cross the axis so closely together (note rapidly decreasing spaces between reflected arrow of B, and that of A) that the visual definition of objects like the moon and things on the earth may result roughly as clear as if the mirror had been parabolized. That is why the method described in Part VII is included in this book, and it is believed that while those who make a spherical mirror will find it fairly useful, they will gain further incentive to learn how to parabolize a scientifically correct mirror.



THREE COMMON CURVES. FOR EXPLANATION, SEE OPPOSITE PAGE.

The upper half of the diagram referred to, shows how parallel arriving rays are reflected from a paraboloid, which is a curve whose radius, unlike that of a sphere, shortens continually as the axis is approached. Here again the angle of reflection of each ray is the same as the angle of incidence, but


Mirror (6" 4' F.L)
Nov 21, 25. Springfield Vt.

Time	Stroke	Ap. Sections	Remarks.
Nov 21 0	0		
10m	2" (Elliptic)		Ring laps
Nov 23 10m	2"	3/4"	
15m	2"	5/8"	do
15m	2"	1/4"	" do
15m	2"	3/16	do
7m	3", elliptical		Flat. Parabolized

A SAMPLE RECORD OF WORK

It shows how a hyperbolized mirror with turned-down edge, due to use of too long a stroke, was treated and brought to rights. Such a record should be kept from the very beginning. It will prove invaluable in making the next and larger mirror.

the changing radius of curvature of a paraboloid compensates for this and brings all of the rays exactly to a single point—the focus.

The hyperboloid is still deeper than the paraboloid, having a shorter radius at the vertex. It does not bring the reflected rays to a single point, although for the sake of avoiding confusion the reflected rays were omitted from the drawing.

Regarded from the aspect of the making of specula, these three curves should be shaped so that they all start together at the vertex and cross each other at the edge of the speculum. To have done this here would, however, have added confusion to the drawing. If one has time, it is well worth while to hunt up one's dusty school books and lay out a curve of each type. Enough of the working lines were purposely left or indicated, so that the student can reconstruct the method, by prolonging them until they cross. There is a set for each curve, based on equal divisions of unequal spaces, horizontal and vertical.

"The two arms of a parabola are more nearly parallel as the distance to the right increases, and approach parallelism as the distance to the right approaches infinity. If the arms of the parabola are opened out so that they are no longer ultimately parallel, we get the hyperbola."—Moulton.

It is advisable to keep a systematic record of one's spells of grinding, polishing, and especially of figuring, for such a record will prove invaluable if a larger mirror is attempted later, as is likely. A typical record showing how a hyperbolized mirror was remedied, is shown on the opposite page, not only as a sample but in order to show how an expert "doctored" a mirror which was brought to him with a hyperbolic figure and a turned-down edge, both of which had resulted from the use of too long a stroke in fine grinding.

The first line of the record shows an apparent section like that described in Part I, Ch. I (hyperbola). The center was now shaved away from a pitch lap, leaving a ring, and an effort was made with this tool to move the ridge of the apparent cross-section farther toward the center, using an elliptical stroke. This proved unsatisfactory, so it was decided to bring the mirror to a sphere and parabolize from that. With a pitch tool pared like the one shown in Part II, Ch. 5, and using a two-inch, elliptical stroke, the surface was gradually planed down to an apparently flat plateau (sphere), leaving, however, the turned-down edge. More planing narrowed this edge until it, too, disappeared. (Note that a central pit developed and disappeared again during this process.)

Finally when the mirror was spherical practically all over, it was parabolized in only seven minutes, using a three-inch, elliptical stroke. (Here the stroke was lengthened for it was *desired* to deepen the curve.) Only an old hand should attempt to go ahead and parabolize in so short a time, or in a single spell, without frequent testing.

"While many amateurs advocate coating their laps with beeswax or paraffin, or mixing these with the pitch, it is a significant fact," says Porter, "that Brashear, whose establishment has produced most of the finest optical surfaces in this country, used nothing but plain (strained) pitch.

Cloth laps are sometimes used. Felt or broadcloth is cemented to the glass tool with hot pitch and is pressed into shape with the speculum. Polishing is done with rouge and water as usual. But the surface produced in this manner is never as good as that produced by pitch; it is slightly wavy. The poorest work of this kind is called by the mirror-working fraternity, 'a lemon-peel finish.' Pitch starts in work by *shearing* off the tops of the irregular elevations left by the fine grinding; the valleys between are

not touched until, at the last, they—that is, the few remaining pits—vanish as if by magic. It is estimated that any effort to bring a surface nearer to perfection than a quarter of a wave-length of light, viz., 1/200,000 of an inch, is time wasted. This amount—five millionths of an inch—is just detectable with the knife-edge test."

Do not swab off the mirror with waste, for this is generally full of sharp grit. A two-ounce roll of absorbent cotton—a standard drug-store size—can be cut into a number of four-inch lengths, and if each length is rolled up separately in paper, and kept rolled up until needed, it will be free from grit. Paper towels used like blotters are also excellent for cleaning the mirror.

Melted pitch will not strain through muslin. Use cheese cloth, and double it once or twice. This removes any grit that may be in the pitch.

Attach a long stick of wood loosely to one end of the rack on which you place the mirror during the knife-edge tests. This will enable you to control its position from the testing position several feet away, an invaluable aid.

Soon after rouge polishing begins, the Foucault shadows may be seen.

Sometime, while testing the speculum, lightly place the finger tips on its face for a few seconds. When quickly viewed from the knife-edge position, the "hills" due to expansion under your warm finger-tips will all stand up sharply. This trick always impresses visitors with the delicacy of the Foucault test. Also, have someone hold his hand below and near the speculum while it is in the testing rack: the waving currents of air due to the heat of the hand are a revelation!

Experts advise keeping the eye very close to the knife-edge during testing, even removing one's eye-glasses—provided it is possible to see without them. To discover why the eye must be kept close, first place it close, then move it slowly back; the mirror apparently becomes covered with black radial streaks. This is an unavoidable condition existing in the human eye itself.

If the grinding stand is not quite level, no harm will result: you will always get a perfect figure of revolution, because you keep turning the tool and the mirror around from time to time by varying amounts.

It is convenient to keep the coarser sizes of carborundum in a large, cleaned salt-cellar; the finer sizes may be made up into a cream before using.

While Porter advises the use of sizes 80, 120, 280, 400 and 600 carborundum, Ellison recommends sizes 80, 200 FFF, 400, 500 and 600. While these seem contradictory, what we have in both cases is simply a series of grains regularly diminishing in size. Either group is equally suitable.

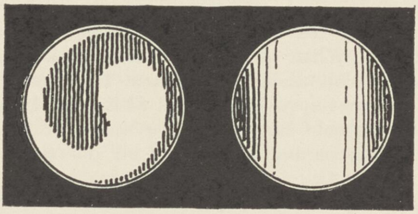
Unlike common "looking glass" mirrors, it is the face (concave) of the telescope mirror which is to be silvered.

The sharp edge produced in case the disk becomes ground down excessively is liable to chip off and scratch the mirror. Hone or chamfer this edge off with a carborundum stone, washing the mirror thoroughly afterwards.

Should the disks become stuck together, try a wooden mallet. A hardwood lever with chisel-shaped end, inserted at edge notch, and pried carefully over a fulcrum, may lift the mirror. If necessary, melt out the pitch in water warmed and heated very slowly and make a new lap.

The remainder of the Miscellany consists of notes prepared for the present (second) edition, two years after the previous notes were written. Many of these new notes have been directly inspired by requests for help made by other amateurs; also by practical difficulties encountered by The Editor in his own work. Abstracts and extracts from scattered and often obscure books and articles bearing on telescope making follow later, and it is hoped that some of these will prove useful to the advanced amateur who wishes to explore beyond the beaten path.

Warped Mirror: The shadowgraph characteristic of a warped or "twisted" paraboloidal surface is similar to the emblem of the Northern Pacific Railroad, known as the "monad." A mirror showing this figure persistently should, according to Porter, be treated as follows: Seek out a good hard, solid hydrant. Hurl the mirror as fiercely as possible at said hydrant. Walk home. Such a



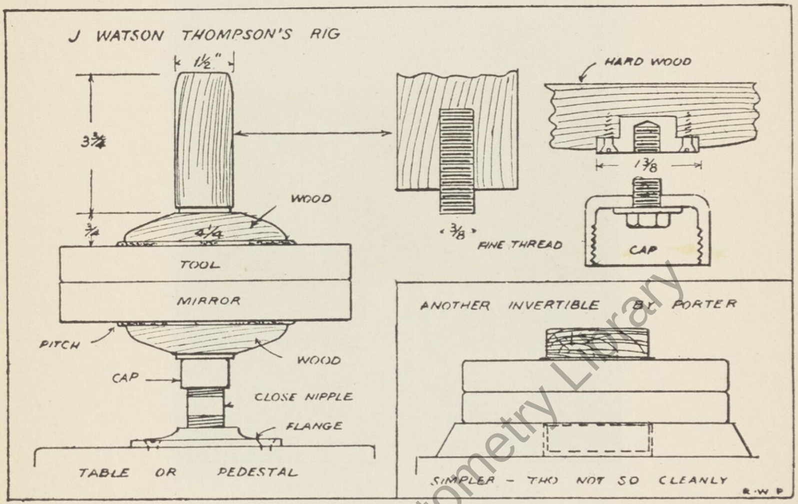
DISTORTED MIRRORS

mirror is strained and is hopeless; the glass was not well annealed. Fortunately, this kind of thing seldom happens.

Astigmatized Mirror: Suppose the shadow comes in from both sides at once, making two half moons of deep shadow, one on either side. This indicates that the mirror is no longer a figure of revolution but an oval; it has astigmatism. One must go back to fine grinding again, then polish a few minutes and test. If it still shows oval, the chances are that there is a weak diameter, the glass was badly annealed and the disk is hopeless. Only one case of this kind of tragedy is known to The Editor, so far.

Needless Efforts: There is no need of making a slavish duty of "walking around the barrel" while grinding and polishing. One may safely stop in one place and take 10 or 20 strokes. Because one does not then have to think of constantly shifting, more pressure can usually be brought to bear on the disk and excavation will be accomplished in proportion. There is no danger of getting the curve lop-sided by this method. But when it comes to polishing, this method will usually give a surface which under knife-edge test appears lumpy, like that of a "dog biscuit." Therefore, just before getting ready to test, taper off by taking successive groups of, say, 8, 4, 2 and 1 strokes in a place. This will even up the surface. There is no objection to sitting down to work, provided the tool be turned a little now and then.

Inverting Tool and Mirror: In grinding, Ellison gives instructions to allot to certain sizes of carbo. certain reductions in length of radius. An alternate method is to employ a rig which will permit quick inversion of mirror and tool—*i.e.,* tool either on top or on bottom, at will—and then excavate all the way to ultimate radius with the first size of abrasive. From then on one may hover more or less around that radius by alternately inverting and re-inverting. This also brings plenty of work on the outside zone of the mirror, which ordinarily polishes out last and, therefore, needs it. With this method, however, one must be on the watch for turned edge, due often to the application of force too high up on the handle. As finer sizes are used, make the simple pencil mark test for sphericity, by carefully drying and cleaning the tool and mirror,



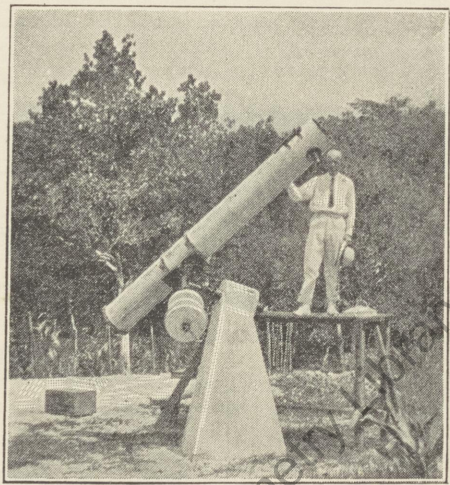
INVERTING DEVICES

It is a marked convenience to be able to invert tool and mirror, and without time-consuming bother

drawing pencil marks across each, working them dry with a few very short strokes and observing where they are in contact by noting where the marks are rubbed thin or entirely off. To get rid of the turned edge, which probably amounts, when noted at this early stage, to what would be considered grossly and incurably turned if permitted to pass on to the polishing stage, remove the handle and grind a few wets with strokes less than one inch long. It is well, if this more elastic method of reaching the desired radius by inverting tool and mirror is employed, to arrange to leave an inch or less of radius at the end for polishing, and to do most of the polishing right side up, thereby avoiding possible turned edge from that source and perhaps facilitating the observation of

contact with lap by permitting the worker to look through the glass while polishing is in progress.

Inverting Device: For those who really enjoy elaborating the few simple tools needed for telescope making, a rig for hand grinding and polishing, made by J. Watson Thompson and presented to The Editor, may be constructed—provided one has a lathe. This has proved entirely satisfactory and most convenient when it was desired to invert the normal positions of the tool and mirror. The sketch explains it. It also has the additional advantage of keeping the work up out of harm due to grit from the usual bench or pedestal. A common pan with a hole cut through the bottom for the stem of the stand is



A HOME MADE TELESCOPE

Made by Professor George H. Hamilton of Jamaica (note low angle of polar axis, for use in 18° N. Latitude). The owner also made a 12 inch, and has commenced a 21 inch. Described in the Scientific American, January, 1928, pages 46-47.

usually placed under it. This catches all drippings and can be cleaned up in a jiffy. Another advantage this rig embodies is variable height—obtainable by inserting pipe nips of various lengths in the upright stem. The wooden flanges shown in the drawing are a slight variation of Thompson's original job, in which disks only about 2 inches in diameter were used. These do not "blindfold" the mirror while it is being worked (you can see the contact through it), but they did not, at least in one man's hands, provide enough area to keep the disk from breaking off under stress of hard work.

Sticking Mirror: Bubbles that form between mirror and tool may be pushed

out if one wishes, simply by sliding the top disk away out over the lower one and then carefully drawing it back; then the same on opposite side. Occasionally a mirror will stick and suck, even during fine grinding. If the disks are spherical and have an equal radius they will not stick (although any mirror ought to push a little harder as it passes over the other, for more surface is in contact at that part of the stroke). If the disks stick they may be badly hyperbolic. If the latter, they cannot make good contact at ends of strokes, there is a tendency to create a vacuum between them, and this will account for the sticking. A very short stroke—sometimes less than an inch long—will usually doctor any such condition in a few minutes. "Or," Porter states, "one may

A GOOD OBSERVING STAND

Made by Professor George H. Hamilton. It is light and rigid. Being sectional it permits adjustment to any desired height of eyepiece. Note the overhanging shelf next the telescope. This facilitates standing close to the eyepiece.

press down locally at the *edge* of the mirror as it revolves under his hands, thus wearing away the edges of mirror and tool and bringing their central portions back again into contact."

Laps in Hot Places: In the tropics, pitch may refuse to perform well, due to the heat. Vard B. Wallace used resin tempered with beeswax while making a telescope in Guatemala. Professor George H. Hamilton of Jamaica, British West Indies, author of *Mars at Its Nearest* and the maker of two telescopes described in the *Scientific American,* January, 1928, has had considerable experience with laps in warm climates.

Uniform Working Temperature: When the advice to work in the cellar is given it is not to be inferred that one who has no cellar cannot make a telescope, provided he can find a warm workshop that stays at fairly uniform temperature—say, within 5 degrees or so. As Ellison says, it is changing, not changed, temperature that plays havoc with the job. If forced to use a warm place one must, of course, experiment with harder laps of boiled-off pitch or some of the materials suitable for the tropics.

Describing Cold Pressing, Ritchey says, "When it is sufficiently pressed the surface appears uniformly smooth and bright." Incidentally, this points out the value of keeping the back of the mirror relatively free from blindfolding obstructions, so that one can see what goes on at all stages of the polishing.

Turned-down Edge: Ritchey forestalls turned-down edge by "diminishing the area of the squares around the edge of the tool, by trimming their edges." On this, Porter comments, "It is O.K. Have done it frequently to advantage."

Substitutes for Pitch: As soon as the first edition of the present work appeared, several amateurs experimented with other substances than pitch for laps. H. L. Rogers and a co-worker coated a pitch lap with ordinary Johnson's Liquid Floor Wax, giving it two coats (very even and very thin). Rogers states that a fine polish was obtained. A variation of this was to dry the liquid wax over a gas stove. The lap and mirror were kept in a bowl, just covered with water, when not in use, thus maintaining the lap in perfect condition.

"Pitch," says Wegener in *The Origin of Continents and Oceans,* "behaves as an absolutely solid body when subjected to blows and percussions, but, given time, it begins to flow under the influence of gravity; a piece of cork cannot be forced through a sheet of pitch, but after a lengthy period its slight buoyancy is sufficient to allow it to rise slowly through the pitch from the bottom of a vessel." He goes on to observe that pitch is harder than a candle, yet if one lays a stick of pitch and a candle horizontally between two supports, the pitch will bend of its own weight while the candle will not. According to definitions given in Maxwell's *Theory of Heat* (1872), the candle is, therefore, classed as a "soft solid," while the pitch is a very "viscous fluid." For an interesting article on pitch, by F. W. Preston, see *Transactions of the Optical Society,* No. 3, 1922-1923.

To Adapt an Old Lap to a New Job, or to bring a very badly fitting lap into contact, dip it into warm water a few seconds and begin polishing at once. The mirror may likewise be similarly warmed. But beware of icy drafts.

Prolonged Cold Pressing: When a wet cloth is left around the mirror during cold pressing it dries out very rapidly because the cloth acts like a wick, bringing the unevaporated water to the surface. The Editor has found useful for preventing this occurrence the rig described on page 205, at center, "To keep . . . . . etc." See that the joint at the bottom is fairly tight and you can leave this rig almost indefinitely with safety.

Channels in Laps: What is the purpose of cutting channels in the pitch lap? We often hear that they are for facilitating the spread of the rouge.

This is true, but there are two other and at least equally important reasons. The channels admit air, and thus break up sucking or adhesion of the mirror. But, most important of all, they permit contact to be established by cold pressure, for they provide the pitch with a place to escape to when it is slowly deformed under pressure. Without them the pitch would have to flow clear out to the edges of the tool. With this in mind, it should be apparent that shallow, half-hearted channels do not greatly facilitate good contact. Cut them

A HOME MADE TELESCOPE

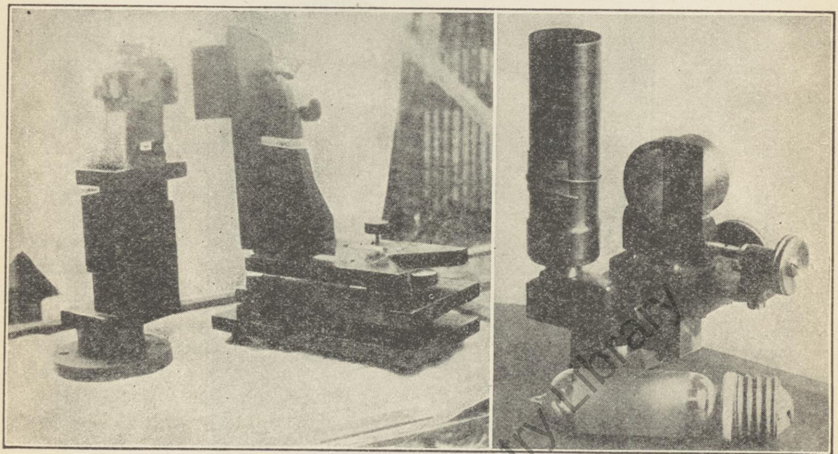
J. A. Johnson, Opt. D., made this rather unusual instrument which was described in the Scientific American, August, 1928, page 172. The mirror is a 10 inch, of 72 inch focal length. The telescope has setting circles. Study the pedestal; it contains an elaborate clock drive made by the owner. The housing of the telescope moves aside on two tracks.

down to the glass itself—they will fill in rapidly enough by slow flow, while one is working.

Test for C. of C.: Many have passed up Ellison's test for center of curvature (page 78) because it is "hard to perform," "awkward," and so on. If one will persist it will soon become simple enough, just as is the case in learning to do anything new. Used in coarse grinding, it will give the center of curvature within 3 inches, and in fine grinding, down to an inch or sometimes less. The

test is a valuable aid. An electric flash lamp is splendid for this test. Quick motions of the lamp will often betray what deliberate ones will not. Another method is to take the mirror, wet, out into the sunlight and see where the reflected disk of light (at focal plane) is least indistinct. This test, of course, gives focal length, not radius of curvature.

Tubeless Telescope: If one is forced to observe near strong street lamps, or if one wishes to use his telescope as a terrestrial instrument, the tubeless mounting described on page 28 will not function any too well, the view being somewhat fogged by the outside sources of light. It is better to employ a tube for these purposes.



SLOW MOTION DEVICES FOR TESTING

The one in the left hand photograph was made by Henry H. Mason, from a description by Rev. C. D. P. Davies, in Monthly Notices, Royal Astronomical Society, March, 1909. Hinges and thumbscrews permit motion in two planes and there is a fixed magnifying glass with which to read the scale. The lamp is also shown. The apparatus in the right hand photograph is described in the text. The annular ring takes a standard eyepiece when the eyepiece test is to be made. The knife-edge is attached to it merely by wax and may then be removed. Apparatus of the kind shown in these photographs is not required, but some enjoy constructing it and it is useful.

Electric Lamp for Knife-edge Test: Near the bottom of page 205 the statement was made (originally in the first edition) that the knife-edge test could not be performed with an electric lamp. However, a method has been found—and a most simple one at that—by J. Watson Thompson, a lawyer. He simply frosted the lamp bulb with carbo. The resultant illumination through the pinhole was perfectly uniform when seen on the mirror. It would be well, however, to see to it that the pinhole does not come quite opposite the actual filament of the lamp. A 110-volt, cylindrical candelabrum lamp bulb about an inch in diameter was employed, having straight sides and a miniature base. The

lamp is easily frosted by daubing it with No. 220 carbo., wrapping around it a strip of thin sheet metal and working it in the hand a few minutes. By purchasing an "adapter" the miniature base may be made to fit standard lamp sockets. One may fill in the "throat" left around the base of the lamp with plaster of Paris, in order to hold the bulb more firmly. This bulb is simply introduced from above into a piece of tubing perforated for the pinhole. It is a great convenience thus to do away with the mussy oil lamp. In localities where the voltage is a bit high the lamps may burn out very quickly. This is because they become too hot in their prison, electric lamps being designed for a normal amount of air cooling which they do not get when inside of the tube. Here it may become necessary to insert a small resistance in series into the line, to ease off the voltage a little bit. The new inside frosted electric lamp bulbs can be used to almost equal advantage.

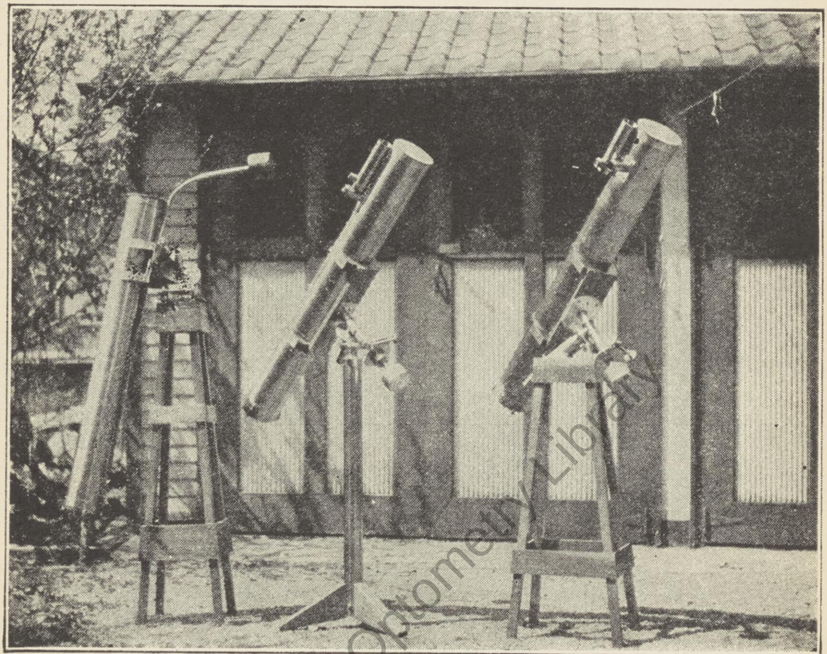
Tiny Pinhole for Advanced Workers: Prof. Ritchey says: "When the knife-edge test is used with an extremely small pinhole of between 1/250th and 1/500th of an inch in diameter, illuminated by acetylene, or what is much better, oxy-hydrogen or electric arc light, minute zonal irregularities are strongly and brilliantly shown, which are entirely invisible with large pinhole or insufficient illumination."

Sleeks (minute patterns of scratches visible only in favorable light and at certain angles) may often be removed by a few moments' polishing on the dry lap. Another method is to start polishing on them with short strokes and scarcely any rouge, and gradually increase stroke and amount of rouge.

Avoiding Scratches: Newspapers are cheap and can be used to good advantage to prevent scratches on the mirror. One may lay or tack them on tables and all places likely to harbor coarse grains of abrasive, and then tear off a page or two with each change to finer abrasive. It is well to be fussy about not getting carbo. on tool handles, etc., from which a few coarse grains may easily be picked up later on. Any rag or towel that may be used as a general sop-up around the shop is a likely culprit. Ordinary cotton waste is safe for swabs only during coarse grinding but not for fine grinding, as it often contains grit. Here it is best to use absorbent cotton (see page 211, near top). For drying mirrors The Editor uses paper towels or a handkerchief. In favor of the latter is the fact that the same handkerchief is not likely to be in one's pocket long enough between trips to the tub to carry coarse grit over to the next finer stage of grinding. Worst of all habits is that of wiping one's hands on one's work clothes, for these are usually worn throughout several stages of finer and finer grinding. Old hands at mirror making appear careless about grit. This is an "optical illusion"—they know just when and just where they can get away with it without risk of scratches. Until one has become wise it is better to play safe and be fussy.

If one has reached the last stages of fine grinding and is worried about scratches, it is just as well not to start off each new wet with a long stroke, for if any coarse particles were present this would drag them clear across the mirror. But a group of very short strokes will at least localize such scratches and the offending coarse particle will generally be broken down quite quickly.

Even this is, however, a botch or makeshift and contaminated carbo. should really be washed. Transfer it to a common drinking glass (clean), stir it up and observe how fast it settles. As the heavier particles are to be sorted out by taking advantage of the fact that they settle more rapidly, we strive to pour off or syphon off the water into a second glass after the right lapse of time, leaving behind any coarse particles. A bit of preliminary experimenting with this process will teach more than a ream of words.



THREE HOME MADE TELESCOPES

Made by H. L. Rogers and described in the Scientific American, November, 1926, page 373 and November, 1927, pages 468-469. The one in the center shows the ingenious finder described elsewhere in the present volume. Rogers became interested in the work when Amateur Telescope Making was first published, and since that time has made a number of telescopes.

How Long Is a Wet? In grinding, the best test for the proper length of a wet is when the grit stops sounding gritty. If one is of an investigative turn of mind and has a medium-powered microscope it is interesting to start with a charge of fresh carbo., grind 20 or 30 strokes and examine a dab of the charge under magnification, noting how the grains have broken down and how many particles of glass are commingled with the abrasive. Carry this out until the

carbo. is all broken down and glass predominates. It will prove instructive and worth while.

Abrasives: Besides carbo. there are several excellent abrasives, each of which has its warm adherents. Aloxite, made by the Carborundum Co., is one. John Pierce uses Nos. 80, 120, 280 and 600, and follows up with a dose of No. 304 Garbite made by the Hubert Optical Abrasive Co. J. Watson Thompson recommends the Bausch & Lomb Optical Company's abrasives, Nos. 900E, 902E, 904E and 906E. He also uses "magnetic black rouge," obtained from Binney and Smith; we have never tried it. Porter and The Editor have made preliminary trial of a new abrasive prepared to the formula of the British Scientific Instrument Research Association, called "Sira". The manufacturers, R. and J. Beck, Ltd., recommend that it be used directly after grinding with No. 80 and one minute carbo. The Editor tested "Sira" against carbo. under identical conditions, on the same piece of glass ground on either side with one minute carbo. and followed on one side by No. 600 carbo. and on the other side by Sira. The former gave a surface which reflected the filament at 10 degrees (see page 204); the latter at 12 degrees, and a finer surface with pits more uniform in depth. Porter states: "I have just used your new Sira on a batch of 24 small lenses. It is true that it starts in after carbo. No. 220 and cuts fast and is then ready for polishing. It's good stuff all right. But we use *finally* Bausch & Lomb No. 906E (emery), which seems to give a little finer surface." Sira comes in 3-pound tins at one shilling, tenpence. Import duty payable at local postoffice. Another kind of abrasives are those made by the American Optical Co. These are numbered M301, M302, M302½, M303, M303½.

Crushed Steel: Some prefer to rough out with crushed steel. This may be purchased from the Pittsburgh Crushed Steel Company. J. W. Fecker advises the use of No. 90. It cuts very rapidly but leaves deep pits. Hence it is suggested that, in roughing out, the abrasive be changed to No. 60 or No. 80 carbo. when the curve is about halfway down; certainly not over two-thirds way. Take care, however, that all traces of the crushed steel are removed when through.

Correcting a Hyperbola: Working with a pitch lap, H. L. Rogers states that he has successfully reduced a hyperbola, simply by painting a ring of rouge on the outside inch or so of the tool, keeping the remainder of the tool just wet enough to slide nicely, and using short strokes.

Chamfering of Disks: Sometimes the disks when received are not chamfered on the edges, and sometimes one will quite wear away the chamfer, leaving a sharp, delicate edge. This edge is liable to chip off and the chips are more than likely to scratch the surface. Accordingly, the business edges of both disks should be honed with a carborundum stone held at an angle. In the average case The Editor finds that a bevel carried one-sixteenth inch back from the edge will nearly but not quite grind out—for we wish to leave a small width of bevel on the finished job. It is not so well, however, to put off chamfering until later, for tiny round chips are likely to be flaked off from the surface near the bevel, and polishing or even fine grinding will not excavate enough

glass at the edge of the disk to work them out. It is best to do the beveling at the start; and then keep an eye on it in order to increase its width if necessary before the job has progressed too far.

Thickness of Glass Removed for Each Stage: While we are plugging away with the various stages of grinding we shall want something to think about. And here is something: How much actual depth of glass does each stage of grinding ordinarily remove? And especially, how much removal of glass does polishing involve? If we know these amounts, even in round numbers, it will frequently be of use to us, improving our judgment when it comes to making certain decisions.

To arrive at these figures by calculation is easy. Knowing the radius for each stage of grinding and polishing, we simply substitute in the formula $r^2/2R$. This is none other than our old playmate, the r^2/R formula, altered a bit because here we are no longer dealing with a beam of light whose aberration is doubled by reflection (which accounts for the R, instead of 2R) but determining the actual depth of the curve with regard to a straight-edge placed across the surface of the mirror. This depth is called the "sagitta," the Latin word for arrow (the line of the sagitta perpendicular to the center of the glass resembles an arrow held on a bow).

Let us assume that we are working with a 6-inch mirror having a radius of 96 inches. Assume, also, that we reduce the radius of curvature to 132 inches with No. 60 or 80 carbo.; 22 inches more with No. 100; 10 inches more with No. 220; and about an inch more with each successive size; finally alloting a generous inch to polishing. We substitute in the formula and obtain the following figures:

Carbo. No.	*Radius*	*Substitution*	*Sagitta*	*Difference*	*Or roughly*
60	flat to 132″	9/264	.03407″	.03407″	1/30 inch
100	132″ to 110″	9/220	.04090″	.00683″	1/100 inch
220	110″ to 100″	9/200	.04500″	.00410″	1/500 inch
280	100″ to 99″	9/198	.04545″	.00045″	1/5000 inch
400	99″ to 98″	9/196	.04591″	.00046″	1/5000 inch
600	98″ to 97″	9/194	.04638″	.00047″	1/5000 inch
Rouge	97″ to 96″	9/192	.04682″	.00044″	1/5000 inch

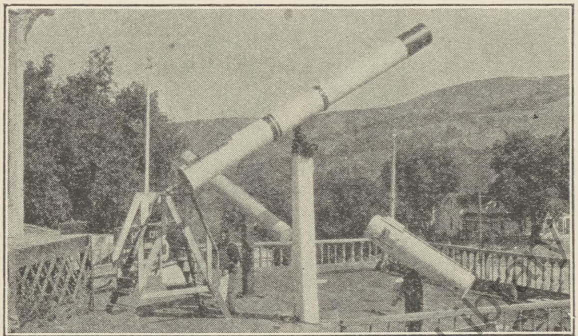
Thus we see that we have worked about as hard to excavate 1/5000 inch with one size carbo. as we did to remove 1/100 inch with another; and about five times as hard to polish off the last five-thousandths of an inch with rouge as we did to remove the same 1/100 of an inch with carbo. As a matter of fact, these are not, strictly speaking, the actual depths of glass worn away, but rather the differences between the amounts worn away at edge and center of disk. (Probably half as much glass is worn away at the edge as at the center.) But no matter—we now have in mind a rough idea of the amounts we are dealing with for each stage of the job, and these amounts will apply in a general way to most of the mirrors we are likely to undertake.

Finally, in altering our final sphere to a paraboloid, how much do we actually scoop it out? A mere 50,000th of an inch! For the inside zone of the

parabolized mirror has about one-tenth of an inch shorter radius than the outside zone; and we may thus calculate the amount of deepening by the same formula as above.

F. W. Preston of the Research Laboratory of Messrs. Taylor, Taylor and Hobson, Ltd., states that in their workshops it is known that there is commonly removed in the polishing process from 6/100,000 to 12/100,000 of an inch in thickness. It is found, he says (*Trans. Opt. Soc.,* No. 3, 1921-22, p. 159), that with automatic polishing, and when the polisher is working at its best, this amount is removed in 50 or 60 wets. Consequently, the average amount removed per wet is in the neighborhood of one or two millionths of an inch.

In Grading Carbo. it was found by Dr. J. W. French that the grains fell through water at a velocity directly proportional to the diameter of the par-



HOME MADE TELESCOPES

The three reflectors shown were made by Messrs. Herron and Ferguson of the "Amateur Telescope Makers of Los Angeles." See Scientific American, March, 1928, pages 244-245.

ticles. Theory calls for a fall proportional to the square of the diameter. But many a fine theory is exploded by a mere fact. (*Trans. Opt. Soc.,* Oct., 1917, article on grading carbo.)

Range of Size: If rouge be left in water 10 to 15 minutes the particles remaining in suspension will have an average diameter, according to Beilby, of 1/50,000 to 1/30,000 inch. This compares roughly with the average wavelength of light. Beilby believed these particles were actually aggregates of cohering units which would probably be reduced under work to finer form. The microscope will resolve scratches made by an abrasive down to about 1/100,000 of an inch in width, unless strong dark-field illumination is employed, and a wavelength of violet light—the shortest of the visible rays—is just about 1/100,000 of an inch.

Keep a Log Book: Write down in it everything you do. It will prove invaluable on subsequent jobs, especially if they do not happen to follow closely

on the heels of the last one. It is well to jot down various "don'ts," just when the situation arises that provides the don't. Then, some months later when you tackle the next mirror you will read this record, discover your mistakes, profit by them and get off to a flying start. There is still another reason for recording everything: amateurs of the future may come to treasure your records—should you evolve into a Herschel, a Ritchey.

Limiting Devices: Every now and then someone devises an automatic limiting device for insuring strokes of uniform length, or one for turning the tool by some even part of the circle. These ingenious devices are worse than useless, for the very merit of hand work is that the combination of stroke length and direction is never twice repeated, thus preventing the development of zones, etc. On the other hand, no slavish effort should be made to vary the length of strokes. This will take care of itself.

Take Courage: With regard to his mirrors Ellison is exceedingly particular, and it has often been suspected that the little paragraph at the top of page 89 has been responsible for scaring off many a prospective telescope maker who did not know that a mirror may fail by quite a lot to come up to Ellison's high standard of perfection, yet function so well that the difference would not be worth the price of throwing up the sponge at the outset. Sir William Herschel's many mirrors were recently brought to light and given a knife-edge test. Some of them proved to be what a modern amateur would call "not so good." Yet they functioned passably well in use. Sir William did not have the advantage of the knife-edge test, but worked by feel alone. Foucault had not yet discovered his famous knife-edge test. If you are wavering, don't let Ellison's criterion of perfection scare you off.

Getting Contact Before Polishing: There is one place where Ellison might to advantage have been more explicit. Near the bottom of page 77 he recommends the use of the long (full) stroke for roughing out. This is good, not merely because it saves much work and time, but because it leaves the outer zone of the disk comparatively untouched while a shorter, roughing-out stroke would bring nearly as much work on the outside zone as on the center and thus take quite an appreciable total thickness off the mirror—a point which may become important if the disk is none too thick to begin with. Now, the important point is this: after the long strokes of rough grinding have scooped out the center irregularly, as Ellison says, leaving it a pronounced hyperboloid, the two disks *must* be brought back to *full* spherical contact all over before polishing begins. Preferably they should be brought nearly so before fine grinding. It has been noted that, since the first edition of the present work was published, several mirrors, when finished, proved to be very seriously over-corrected. In two cases the knife-edge test showed that the radius of the outer zone was a full inch greater than that of the inner zone, instead of about one-tenth of an inch (in the case of a 6-inch mirror of f/8). Here the assumption is fairly safe that the hyperbolization came about, not in polishing, but before fine grinding was finished, and was probably due in part to Ellison's failure to stress the point so urgently stressed above.

Watch the liquid sludge through the mirror disk while grinding. This film

of sludge looks thicker than it really is. To measure it roughly, and follow its diminution in thickness from time to time while working, wash both tool and mirror, dry them, brush them absolutely clean with the hand and place a tiny scrap of paper in the center of the tool. Usually the mirror will teeter on the paper to a noticeable extent when it, with the tool, is grasped on either side and between forefingers and thumbs. By choosing thinner paper from a book it is possible to watch the discrepancy between tool and mirror narrow down as the work continues. While a single sheet of India paper is only about one-thousandth of an inch thick, even that is quite a large departure from the spherical if one foolishly leaves it to deal with by means of rouge, whose cutting powers, quantitatively reckoned, are comparatively slight; or for that matter, even with No. 600 carbo.


PARABOLOIDAL SHADOWS

The one on the left is reproduced from the plate which accompanied Foucault's original announcement of the discovery of the knife-edge test. Foucault placed the pinhole on the left, which will account for the location of the shadows on the disk. The picture on the right is a direct focograph made by Dr. Nakamura. See the text.

A way to check up on the scrap of paper method is to draw lead pencil marks straight across both tool and mirror, both being dry; then work them dry a few times with very short strokes. Wherever the tool and mirror are in real contact the pencil marks will be rubbed away. There is no use of proceeding with polishing if the disks are not spherical.

Correct Paraboloidal Shadow: Astrophysical Journal, June, 1918, contains an article by Porter, entitled "Knife-Edge Shadows—Photography as an Aid in Testing Mirrors." A camera was placed behind the knife-edge, at the center of curvature of a mirror, obtaining thereby beautiful "focographs" comparable to what one sees with the eye when making the knife-edge test, but more revealing. A similar focograph made from a 12½-inch Calver mirror of f/8

is reproduced. This was sent to The Editor by Dr. Vi. Nakamura, of the Astronomical Observatory of the Kyoto Imperial University, Kyoto, Japan. Dr. Nakamura, a pupil of Ellison, has produced over 45 parabolic and 80 plane mirrors of high quality. He states that when measured on 10 zones this mirror showed no aberration of more than one-hundredth of an inch. He points out what some may not wholly realize, that the judgment of a surface from the shadow requires delicate estimation. (He is speaking, of course, of really first-class mirrors—let not the doubting beginner become discouraged, for even a poor mirror will provide plenty of thrills when directed on the heavenly bodies, and a better one may be produced either the first time or after further efforts. But even the word "good" does scant justice to Dr. Nakamura's mirrors.) "The paraboloidal shadow," Dr. Nakamura continues, "cannot be judged from its position, but one must study its shape and tones of shadow." He then points out that the shadowgraph on page 10 does not exhibit the proper distribution of light and shadows. This is largely true, though Porter's original photographic shadowgraph from which the plate on page 10 was reproduced does show the proper shadows. The most delicate of these shadows do not reproduce well in a half-tone, but this time the engraver has made a special effort to bring them out. (Incidentally, any amateur who obtains even as good a mirror as the paraboloidal shadow on page 10 indicates is doing very good work and need acquire no inferiority complex.)

We also reproduce the famous drawing by Foucault, which, while it makes poor pretense of depicting the subtlety of the actual shadows, does show very clearly one thing of importance, namely, that the one half of the mirror's shading is precisely complementary to that of the other (with the vertical diameter as an axis of symmetry): *i.e.,* where there is shade on the one half there is light on the other, and in exactly corresponding positions. The late Dr. Calver of England pointed this out very definitely (*English Mechanics,* Aug. 28, 1925, page 96), as does Dr. Nakamura in his letter. If one squints at the Nakamura picture with nearly closed eyelashes this complementary nature of the correct shadows will be better brought out. The manner in which the respective top and bottom horns of the respective dark and bright shadows cross one another should be got clearly in mind.

Finally, and by way of further emphasis, the following is quoted from the Reverend C. D. P. Davies (*Monthly Notices Royal Astronomical Society,* March, 1909): "The one point to be noted above all others is the exceeding delicacy of the shadow. It is impossible to insist on this feature too forcibly. In spite of what Wassell and Blacklock have written, it seems almost hopeless to impress this on the mind of the average worker, who seems to think that because the shadows come on right, he has therefore got a parabolic mirror; the inevitable result of this fallacy being that the tone of shading is in reality far too deep, and the mirror markedly, often profoundly, over-corrected. In most cases the crux of the question lies in the temptation to shirk the trouble of making a proper and effective zonal measurement apparatus and cutting out diaphragms."

Testing by Interference: In *Astrophysical Journal,* June, 1918, Professor

A. A. Michelson, the noted physicist, describes a method of correcting optical surfaces by means of interference fringes. This requires a total reflection prism, a light source, a slit and a 1/12-inch microscope objective, and gives results in hundredths of a fringe of light (1 fringe is about 1/100,000 inch). It is hoped that a few of the more advanced amateurs will try this method and send in their findings, for it looks decidedly interesting.

Don't Forget that when your reflector is complete you are invited to send a brief description of it, with photograph, to the *Scientific American,* for publication. The photograph should be printed on glossy paper, the maker should certainly appear in the picture and especial attention should be given to the background, as nearby shrubs, etc., often introduce a mottled background of lights and shadows which show glaringly in the half-tone or even make hopeless an attempt at reproduction. On the other hand, a large photograph is not required, as the photoengraver easily enlarges to suit the editor's size requirements—provided the picture is sharp and in focus. Some of those published have been enlarged from the smallest sizes.

Optical Glass: Many beginners find it hard to believe that some special, aristocratic variety of optical glass, perhaps made in France, is not necessary for a good telescope. This belief is hard to down. Poorly annealed plate glass is an abomination, but it has certainly not plagued the thousands of telescope makers who have worked from this book for the past two years and used it on successful telescopes. The 72-inch mirror of the great Dominion Astrophysical Observatory's reflector is made of plate glass. Why, then, do some hunt all over the world for special glass? True, on sizes above 12 inches it is time to cast around for special materials—not so much with regard to their composition as to their preparation (annealing, etc.). But the man who has got that far doubtless knows his onions already and needs no such instruction; while this note is intended for that type of beginner whose name is "Doubting Thomas." Of course, there are quartz and Pyrex, and these are still better, but the point is that there is nothing wrong with commercial polished (but not pressed) plate. Both the 60-inch and 100-inch mirrors at Mt. Wilson Observatory are made of a kind of plate glass, and not "optical glass" as the term is generally understood.

At present the Bausch and Lomb Optical Co. is apparently the only commercial institution in this country making optical glass which can be used in constructing optical instruments.

Glass: Enthusiasts who become deeply interested in glass working will pick up more or less valuable information from *The Glass Industry,* a monthly technological journal published in New York.

Speaking of glass making, Hodkin and Consen's *Textbook of Glass Technology* is the last word. While it is primarily for the manufacturer, no one who is seriously interested in optics will fail to profit by a knowledge of glass manufacture. Professor W. E. S. Turner's *Constitution of Glass* is rather advanced.

The Journal of the Society of Glass Technology, published quarterly by the Society of Glass Technology, Sheffield, England, occasionally contains material

of interest to advanced amateurs. It is intended primarily for glass manufacturers. A few large libraries keep this journal on tap.

Wassell and Blacklock Letters: Lest they be lost sight of, mention is made of the long series of letters on mirror making published many years ago in *English Mechanics.* Ellison (page 74) refers to those of Wassell, though they continued until 1886, not merely until 1883, as stated by him. The dates follow: For 1881: Sept. 23; Nov. 11; Dec. 9; Dec. 30. For 1882: Jan. 13; Mar. 24; Apr. 14; May 12; June 16; Aug. 11. For 1883: Mar. 30; Apr. 27; May 4;

A HOME MADE TELESCOPE

Made by E. L. Worbois and described in the Scientific American, May, 1928, page 448. The sights are like enlarged peep-sights on a rifle. This is almost as satisfactory as a finder.

June 1; June 8; July 27; Aug. 31; Nov. 9. For 1884: Feb. 8; May 30; June 6; July 4; Aug. 22; Oct. 24; Dec. 12. For 1885: Feb. 6; Apr. 3; May 29; Nov. 20. For 1886: Feb. 5; Mar. 26; June 4; Sept. 17; Nov. 12. A second series, by Dr. Blacklock, may be found in the volume for 1895, pages 403, 449, 495, 543; and in the volume for 1896, page 26. Much of this matter is out of date, but the dyed-in-the-wool enthusiast who enjoys sherlocking around public libraries

and poring over ancient, dusty tomes in search of hints will enjoy hunting up this series. (Purchasing the back numbers would be a most difficult task. A few large libraries contain them; for example, the Library of the Associated Engineering Societies, 13th Floor, 25 West 39th Street, New York City.) The advanced amateur should not look upon the methods of the old-timers as necessarily sacred, nor consider in the light of a sacrilege a wide deviation from them. This, in fact, is the way progress is attained, for a few such wild stabs in the dark, out of a multitude attempted, will likely land on something new and wholly worth while. One great trouble with mirror making in the past has been that there always has been an "established way", to deviate from which constituted a desecration of a holy of holies. "Try anything once" has proved

A HOME MADE TELESCOPE

Made by E. L. Worbois and shown on opposite page. Folded up for transportation in a car. The mirror is an 8 inch.

a fruitful source of discovery in all fields of science. With several thousand workers doing that, there is no telling what may be hit upon.

Estimating Fineness of Grinding: Dr. James Wier French rates carbo. at four or five times the cutting power of a corresponding grade of emery (*Transactions of the Optical Society,* Jan.-Feb., 1917). It will do no harm to try emery for a stage or two of grinding, just to see what the old-timers were up against before the days of faster abrasives. (The Editor tried it and came away with a profound respect for their patience.) Other notes follow, chosen from Dr. French's article. In working with carbo., emery or sand the abrasive effect, determined by weighing the quantity of glass removed, was found to be directly proportional to the load applied, and is directly proportional to the

speed. Dr. French made interesting quantitative determinations on fine ground surfaces, refining the method described on page 204—"How can I tell?" . . . . etc. He placed his glass on edge upon a table graduated in degrees around its periphery. Near it he placed an electric lamp, permanently fixed. He then placed his eye so as to catch the image of the filament in the glass. "If the plate (*i.e.,* the glass) is rotated," he says, "so as to reduce the angle of incidence, the eye being moved so as to keep the image central, there will be observed at one point an abrupt change in the whiteness of the image, due probably to the scattering of the more intense short wave rays.

"In the first instance some difficulty may be experienced in observing the change, but once it has been observed, no difficulty should be experienced in locating the point of change to within half a degree without the use of any special apparatus other than the graduated circle.

"If now the angle of incidence is still further reduced, the image will quickly become red and then rapidly fade away. The point of maximum redness can be recorded to within three-quarters degree . . . . These two points—where the white image changes and the red is a maximum—afford a definite record of the surface that is independent of the personal element or the intensity of the illumination. Repeated measurements, accurate to within half a degree, can be made of the point at which the image disappears, but as these measurements are not independent of the illumination and the individual, it is necessary to standardize these factors for closely accurate work."

Dr. French determined microscopically that the particles removed in pitch and rouge polishing are about 1/25,000 inch in diameter.

Hardening Brass: The little brass ears at 1, on the prism tube C, on page 29, may be made springy simply by tapping them with a hammer. This hardens brass. To soften brass, heat it in a flame.

Paint for Inside of Tube: A dull or flat black paint is best for the inside of the tube. Ordinary black house paint well doped with boiled oil will do fairly well. Better than anything is "coach black", which comes in cans and is to be diluted with turps, for use. This gives the dull black which one sees on the inside of cameras and other optical instruments.

An Adapter Tube for eyepieces is often a decided convenience, as the length of the eyepiece may not always permit handy focusing. The adapter is a piece of tubing 3 or 4 inches long, into which the eyepiece fits, and which in turn slides within a larger tube—usually the one that holds the prism on its opposite end. Brass tubing that fits other tubing, inside and out, may be purchased from Patterson Brothers or Chas. H. Besley and Co., but one should specify that it must telescope smoothly.

Three in One: If one finds that one enjoys the first job of mirror making, the chances are that one may make several mirrors and learn the art. A good idea, therefore, is to provide for two or three sizes, when making the mounting. For example, in the simple mounting shown on page 29, the board in which the mirror rests can be recessed for 6-, 7- and 8-inch mirrors, each recess being turned out in the bottom of the next larger one. The size of prism should be calculated for the largest mirror.

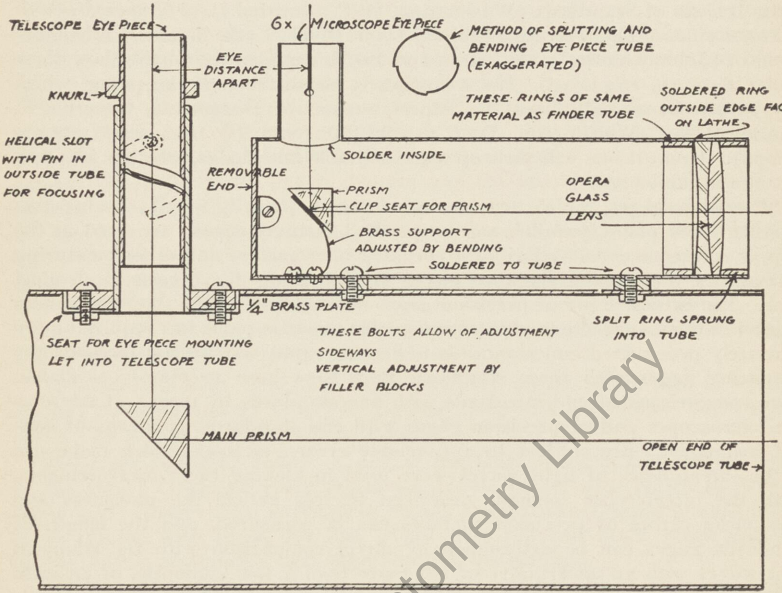
Making a Flat: Some prefer to make their own diagonals and silver them, rather than use a prism; others wish to use a flat for testing at the focus (page 16); another use for a flat is described on page 36; finally, the advanced amateur is likely to make a flat just to find out whether or not he can make a passable one. On page 57 he will find how to go about the task. Of general interest and possible application is the matter of making master flats for testing the precision of machine tools. In all mechanical inventions involving precision work master flats are the final court of reference for the accuracy of gages, micrometers and other measuring instruments. Scientific Paper 436 of the Bureau of Standards (Washington, D. C.) entitled *Interference Methods of Standardizing and Testing Precision Gage Blocks"* (the familiar Johannsen blocks or "Johnny blocks"), by Peters and Boyd, explains thoroughly how these master flats are employed. The following is an abstract of the paper, which may be purchased only from the Superintendent of Documents, Government Printing Office, Washington, D. C.; price 10 cents (do not send postage stamps). From it one will pick up some valuable knowledge, whether he plans to make a flat or not.

"Precision gages, which are blocks of metal (usually steel), having two opposite faces plane, parallel, and a specified distance apart, are used in the shop as reference end standards for checking micrometers and other measuring instruments, and also as distance pieces or size blocks for precise mechanical work. The extensive use of precision gages necessitated by the small tolerances allowed in the manufacture of interchangeable machine parts has required more accurately determined end standards and more rapid and precise methods for comparing gages with these standards than have been previously available. Since comparisons of end standards with line standards by means of micrometer-microscopes and of precision gages with end standards by means of contact instruments are subject to appreciable errors, methods which make use of the interference of light waves were used in making these measurements. With the interference methods described in this article the planeness and parallelism errors of precision surfaces can be measured, and the length of standards gages can be determined by direct comparison with the standard light waves with an uncertainty of not more than a few millionths of an inch. The errors of other gages can be determined by comparison with these calibrated standards with equal precision. This process makes the standard light waves, which have been determined to one part in four or five million relative to the international meter, the standards of length for this work. The apparatus used for calibrating standards and comparing other gages with these standards is illustrated by line drawings and thoroughly explained."

On this subject, see also *American Machinist,* Sept. 1, 1926, pages 329 to 331, by Porter, who has made a number of master flats for various industries. The publisher's supply of back copies is sold out, but copies can be obtained from the H. W. Wilson Company. Most large public libraries also contain the files. Those who have failed to obtain copies of various technical and scientific articles mentioned can, on a pinch, and if the incentive be strong enough, have photostat copies made by some of the larger public libraries, on payment of a fee which will bring the cost of the average article to not over two or three

dollars. The New York Public Library, Fifth Avenue, New York, handles this work by mail, and issues application blanks and a scale of rates. You name the book or article; they do the rest.

Finders: For a finder one may rig up some kind of a gunsight, perhaps employing radium paint, visible at night (The Radium Luminous Material Corp.). In any case, a finder is a decided convenience. One which was purchased from the Gaertner Scientific Corporation for a moderate price proved applicable to almost any telescope and well worth the price paid. A good



Drawing by R. W. Porter

DETAIL OF THE ROGERS HOME-MADE FINDER

one will include a field of view at least 3 degrees (six moons) in diameter. H. L. Rogers, a real estate broker, made his own finder and equipped it with a small total reflection prism. By placing the finder near the eyepiece he was able to use both eyes at the same time in locating a star, an ingenious wrinkle. The Editor asked Mr. Rogers to describe his finder, which he has done as follows: "I took one lens of an old pair of opera glasses of about 1¾-inch aperture, and bought at a hardware store a tube to fit. The lens was seated against a piece of the same tube, split, shortened, faced on the lens side, sprung inside the tube and soldered in. There is an outside retaining ring also, made like the other. Before deciding on the length of the tube the focal length of

the lens must be ascertained (by focusing in the parallel sun's rays, not those of a local light source, and then measuring distance from lens to clearest obtainable image—Ed.). The eyepiece holder for the eyepiece is soldered to the main tube from the inside. Two lengthwise hacksaw cuts divide the eyepiece holder into four prongs which may be sprung inwards to hold the eyepiece. The latter was a low-powered microscope eyepiece smaller in diameter than the 1¼-inch American standard. The sketch shows the prism which is held in a sheet brass clip soldered to a support of stout soft brass. This may be adjusted by the screws and by bending. The end fixture for the main tube is merely a piece of sheet brass with a ½-inch strip soldered across the inside face, and bent at right angles to take a small screw at either end through the main tube. Finally, the finder was attached to the telescope tube at a point so that I could use both eyes at one time in finding an object, a convenience whose unusual value will instantly become apparent on using it. The finder must, of course, be adjusted so that its field of view coincides with that of the telescope. No cross-hairs were used, as it is easy to place the star in the center of the field of the finder, or sufficiently near the center to bring its image somewhere on the main mirror."

To this Porter adds: "It would, however, be easy to add cross-hairs, or at least a kind of sight, simply by bending a piece of spring brass wire into suitable form. If the eyepiece used on the finder is positive, the sight will be snapped inside the tube just beyond the field lens; if a negative eyepiece is used, remove the field lens and place the sight between the two lenses of the eyepiece, against the diaphragm, where it will be in sharp focus. The idea in either case is to place the sight in the focal plane of the eyepiece used."

In one of his little brochures or "hobbygraphs" John M. Pierce tells how to make the objective lens for a finder; and another brochure tells how to make the eyepiece.

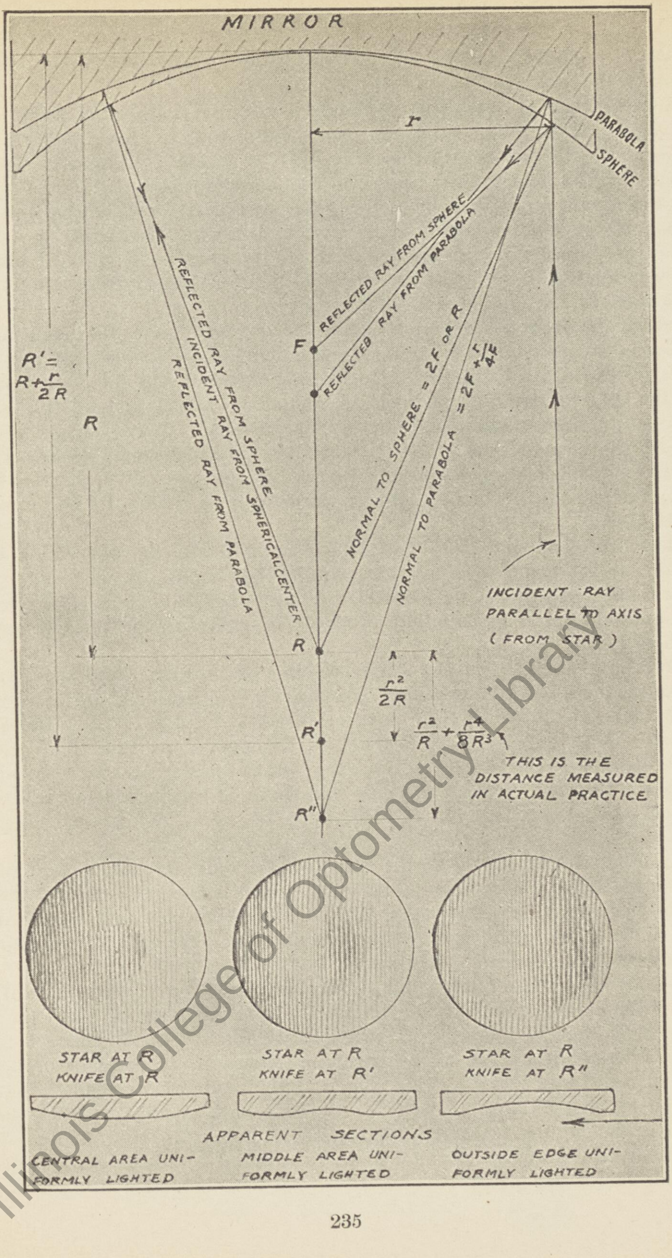
Cemented Glass Disks: Henry H. Mason has been making some interesting experiments in an effort to ascertain whether disks of plate glass cemented together will hold their figure; as it seems to be impossible to get single pieces of plate glass more than 1½ inches in thickness (except by using Pyrex or quartz). He first used celluloid, which melts at 280° F. and sets by cooling; for most of the ordinary cements contain solvents which must evaporate before they can harden, while the large areas involved act to prevent that necessary evaporation. Placing sheets of celluloid between the disks and clamping the disks together, Mr. Mason baked them at 280-300° F. In other experiments Bakelite cement containing solvents was applied to a disk and let stand four hours to evaporate and then treated as above. Ordinary oven baking was later supplanted by linseed oil as being a better medium by which to transfer the heat to the glass, because temperature changes then take place more slowly. Lack of space forbids describing all of Mr. Mason's interesting endeavors, which, by the way, are those of a man in his eightieth year who finds it difficult to write long letters, a point the amateur may be willing to bear in mind if communicating with him.

How Plate Glass Is Made: Polished plate glass and pressed plate glass

are apt to differ in qualities required by the telescope maker. Pressed plate is forced under pressure into a mold and is usually permitted to cool too rapidly to permit good annealing and freedom from internal strains. It can be told by its rough appearance. It is also less expensive—a poor economy, however, for the telescope maker. Polished plate is not necessarily well annealed, at least it is not *necessary* to polish it in order to anneal it; but plate that is worth the cost of polishing actually is always annealed. This is done by slowly moving it through a tunnel 800 feet long called a "lehr," whose temperature decreases from one end to the other. This passage requires five hours. A visit to a plate glass factory would be of interest to the telescope maker, to see how the manufacturer goes at the job of accomplishing on a mass production scale the task which we amateurs do on a small scale and at such cost in physical effort. The molten glass at 2,500 to 3,000°F is poured upon a large steel casting table, a steel roller spreads it out just as a cook rolls out dough, and it quickly drops to a red heat. Then it is annealed in the lehr. Next it is placed on rotating tables and ground by big disks under heavy pressure, with sand and water. Finer and finer sands are followed by several sizes of emery. The polishing is done by means of a battery of 18-inch buffing disks of felt, using rouge. These buffing disks steam under the heat generated by friction. In all, about an eighth of an inch is removed from either side of the glass during these operations. The grinding of a sheet about 25 feet in diameter requires 500 horsepower. From this it ought to be easy to figure out the boiler horsepower of an amateur telescope maker.

Mathematics: While the following discussion of the aberrations of spherical and corrected mirrors may safely be skipped by the tyro as unnecessary, yet those among the advanced amateurs who are mathematical "sharks" will possibly be interested in looking up Prof. F. L. O. Wadsworth's "Notes on the Correction and Testing of Parabolic Mirrors," *Popular Astronomy,* August-September issue, 1902. The title is misleading; the article deals with a consideration of some of the geometrical properties of a parabola, developed by the methods of analytical geometry and calculus. An article by Charles G. Rupert, "Mathematics of the Reflecting Telescope," appeared in *Popular Astronomy,* October, 1918. This will interest the same group of readers. To attempt to abstract either article here would be hopeless.

One point, however, which has caused no little confusion is Draper's original statement that "the longitudinal aberration of a mirror is equal to the square of half the aperture divided by 8 times the principal focal length." This sounds like $r^2/4R$, quite different from our r^2/R, and has been passed down through some of the literature and caused no end of confusion. But here is the catch in it: Draper is evidently speaking of the aberration of parallel rays from a spherical mirror and there is not the least question concerning the practical accuracy of the formula r^2/R as used by Ellison, Porter and others. However, in measuring with a straightedge and scale the actual depth of the sagitta as described elsewhere, the formula becomes $r^2/2R$. The apparent discrepancy between this and the r^2/R formula is explained if one considers that in the Foucault test the ray is a reflected ray; that the angle of reflection always equals the angle of incidence; and that the aberration is,



MIRROR
PARABOLA
SPHERE
r
REFLECTED RAY FROM SPHERE
REFLECTED RAY FROM PARABOLA
F
R' = R + r/2R
R
REFLECTED RAY FROM SPHERE
INCIDENT RAY FROM SPHERICAL CENTER
REFLECTED RAY FROM PARABOLA
NORMAL TO SPHERE = 2F OR R
NORMAL TO PARABOLA
INCIDENT RAY PARALLEL TO AXIS (FROM STAR)
R
r²/2R
R'
r²/R + r⁴/8R³
THIS IS THE DISTANCE MEASURED IN ACTUAL PRACTICE
R''
STAR AT R KNIFE AT R
STAR AT R KNIFE AT R'
STAR AT R KNIFE AT R''
APPARENT SECTIONS
CENTRAL AREA UNIFORMLY LIGHTED
MIDDLE AREA UNIFORMLY LIGHTED
OUTSIDE EDGE UNIFORMLY LIGHTED

therefore, doubled by the curve of the mirror. Reference to the legend of Figure 1, page 1, may help make this clear.

A rough sketch submitted by Clarendon Ions (author of Part VI) and redrawn by Porter will doubtless prove interesting to those of mathematical leaning. In connection with this drawing it is stated: "Draper is right in his statement: 'the longitudinal aberration of a mirror is equal to the square of half the aperture, divided by 8 times the principal focal length,' but is misleading if you don't know what he is talking about. Evidently he is talking neither of pinholes nor knife-edges, but of the aberration in focal plane of a *spherical* mirror, of *reflected* astronomical light; *i.e.,* light from infinity coming in *parallel* to the optical axis of the mirror.

"Since the angle of reflection equals the incident angle, the focal plane will be formed at a distance from vertex of mirror equal to one-half the distance from vertex to axial crossing of a normal drawn from the zone considered. For the sake of scientific precision, it should be added that all this is merely an approximation, within the limits of insensibility. When you get above F/5 or F/4, the accumulated residue or $r^4/8R^3$, will drive you to trig. Roughly, for the central parts of a spherical mirror, all normals of which cross the axis at R, this principal focal length or plane will be R/2. In other words, F equals R/2.

"But when we get away from the central parts, the aberration becomes sensible, and in order to reflect our parallel light from any zone of the mirror, to the same focal plane, we must change the spherical mirror to a paraboloid, the parabolic curve having that property of reflecting all parallel rays to a common focus.

"We have found that the axial crossing of normals from the paraboloid differs from that of the spherical normals, by a quantity equal to $r^2/2R$, and the distance of this point from apex or vertex is R *plus* $r^2/2R$. But since the *principal* focus (F) of the reflected rays is one-half of R in the case of the spherical mirror, the measure of its aberration will be likewise one-half of the difference between its zonal normals and those of the paraboloid whose figure corrects said aberration: *i.e.,* one-half of $r^2/2R$, or as Draper is trying to say: $r^2/4R$ (or $r^2/8F$, as you prefer). So you see he is right.

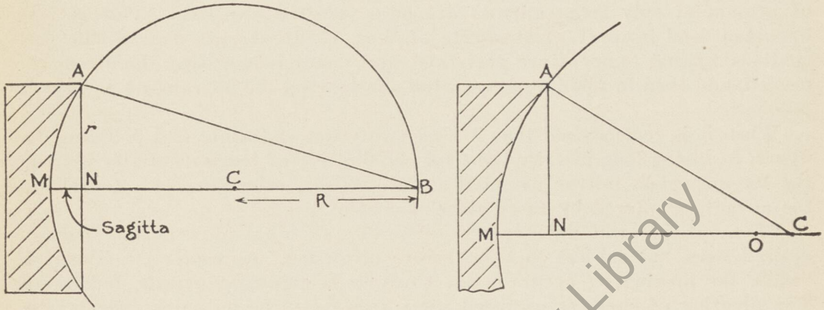
"In other words, you *halve* the now familiar $r/2R$ in dealing with the focus of reflected light from a star (a real one) which is the *astronomical* aberration of $r^2/4R$ of which Draper speaks; just as you *double* this aberration with your *fixed* pinhole, and make it r^2/R in applying the Foucault test, wherein, after all, lies its great delicacy—four times that of a natural star."

Ritchey says, "The illuminated pinhole remains fixed at the center of curvature of the central parts of the mirror, *i.e.,* at a distance 2F from the vertex, where F is the focal length. If the paraboloidal figure is perfect the rays reflected from any narrow zone whose semi-diameter is r are now brought to a focus at a distance $r^2/2F + r^4/16F^3$ back of the plane of the pinhole." In practice the $r^4/16F^3$ term is ignored as involving such small quantities that they would ordinarily be masked by other shortcomings in the mirror. The denominator, 2F, is of course equal to R, as explained under Figure 1, page 1.

John Pierce has prepared a short formal demonstration or "proof" of the

term r^2/R, as follows: To find the sagitta of a spherical mirror, given r equals radius of mirror and R equals radius of curvature: In the figure I, MAB is a right angle, being inscribed in a semi-circle. MN over r equals r over 2R —MN (since the normal to the hypothenuse from the right angle is the mean proportional between segments). But when the sagitta is relatively small, as in a speculum, MN equals r^2.

Another demonstration given by Pierce is as follows: To find the distance between centers of curvature of middle and edge zones of a paraboloid: Draw normals, as in II, from A to M. Then C is the center for zone A, and NC is the subnormal for the edge zone. O is the center for the central zone and MO is the subnormal for the same zone. MO equals NC (since all subnormals of a paraboloid are equal); therefore, OC equals MN. In a speculum, MN approximates the sagitta, and the centers shift an amount equal to the sagitta itself, or $r^2/2R$. If the knife-edge and lamp move together, the shift



I II

DEMONSTRATIONS BY JOHN M. PIERCE

equals OC, these points being the centers of curvature of the edge and middle zones, or $r^2/2R$. But if the knife-edge alone is moved, the shift will be twice that amount, or r^2/R. (Q. E. D.)

Fused Quartz or fused silica is the ideal substance for a telescope mirror, principally because its coefficient of expansion is so very low—only 1/18 that of plate glass—that mirrors made of it can be figured and used under all temperature changes without detriment to the curves. This material was extremely costly until 1924 when the General Electric Company announced that a way to make disks up to 10 inches in diameter had been developed at the Thomson Research Laboratory in Lynn, Mass. Prof. Elihu Thomson, Director of the Laboratory, has been an amateur telescope maker for the past 60 years and he has forwarded the research on fused quartz or silica from that point of vantage. The following statement was prepared by Dr. Thomson:

"For twenty-five years I have borne in mind the great desirability of procuring fused silica disks of glass for astronomical mirrors. It is its low

Even the great Herschel – who might well be called the father of the reflecting telescope – did not know when his mirrors were right until he tried them out on a star. In fact some of them since tried out by the knife-edge test proved to be what a modern amateur would call "not so good" yet they functioned passably well in use.

coefficient of expansion and its consequences which confer such great superiority as the silica disk possesses. This may be stated under several heads.

"1. Disks require but little annealing, while with the large glass this is a matter of great difficulty. 2. They can be rough ground by a carborundum wheel without danger of fracture, an operation difficult with glass and rarely resorted to. 3. The disks can be made very thick and rigid more easily than with glass. 4. The fine grinding (or smoothing before polishing) is carried on with great facility, and the surface before polishing is usually of finer grain than with glass. The fused silica is considerably harder than glass, and not so easily scratched. 5. The polishing proceeds readily and can be carried on regardless of temperature changes. Incidentally, there is less liability of scratches forming in polishing. 6. In very accurate work, figured by polishing, as in high grade surfaces of astronomical mirrors, the polishing and testing need not be interrupted as with glass by long rest periods, with the mirror disk kept jacketed in felt for equalization of temperature. (For the benefit of beginners: only large mirrors are here referred to.—Ed.) This is very important and involves great saving of time. 7. In service, none of the precautions against temperature variations and distortions arising therefrom are needed, and even in solar work with full sunshine on the mirrors, no evil result follows.

When it is remembered that it took two years of testing and polishing for figure, involving long interruptions for equalization of temperature, to produce the 100-inch glass mirror mounted at Mt. Wilson, near Pasadena, California, the advantage offered by fused silica is evident.

"The optician will welcome the possibility of obtaining so-called flats of desired sizes, not subject to temperature distortion," continues Dr. Thomson, "while the making of accurate flat surfaces is evidently greatly facilitated. The silvering of surfaces of fused silica appears to be no more difficult than with glass, with the advantage, however, that the former can be warmed without risk when such warming is needed to assist the formation of the silver deposit."

The manufacture of fused quartz was described in the *General Electric Review* (Schenectady, N. Y.) June, 1924. Disks of from 6 to 10 inches diameter may be obtained, but the present cost of manufacture on a small scale still puts them in the luxury class. Porter figured the first disk after the new process of manufacture was developed and found the figure entirely indifferent to temperature change, whether the disk was worked in sunlight or dipped into hot water and immediately given the knife-edge test. Quartz disks are now being used for various purposes at observatories and in physical laboratories. To take advantage of the non-expansibility of quartz the amateur should, however, be able to work within a fairly close limit of precision. It would be no use, for illustration, to employ quartz for avoiding changes in figure which were already masked by larger errors in the figure.

As fused quartz is expensive, can a tool of plate be substituted? Regarding this The Editor inquired of B. W. St. Clair, Director of the Standardizing Laboratory of the General Electric Company at West Lynn, Mass., himself an amateur telescope maker, who wrote as follows:

"I have delayed answering your letter of February 23rd until I could talk with Professor Thomson himself, as my experience with quartz has been with cast iron laps rather than with glass laps. I discussed this question fairly thoroughly with Professor Thomson who feels from personal experience that there is no difficulty at all in using glass for the tool when working quartz. The Professor points out that it would be necessary to be reasonably careful about the temperature of the glass tool during the final grinding stages.

"I have found from working several pieces of quartz, including one astronomical mirror, that cast iron makes a very good lap material but, as is of course well known, one must be very much more careful about scratching during the fine grinding stages than is necessary when one is using the glass tool.

"Professor Thomson also points out that it might be possible in furnishing quartz disks to furnish two disks. The one to be used as a tool need not be of the same high quality as the one intended for the mirror.

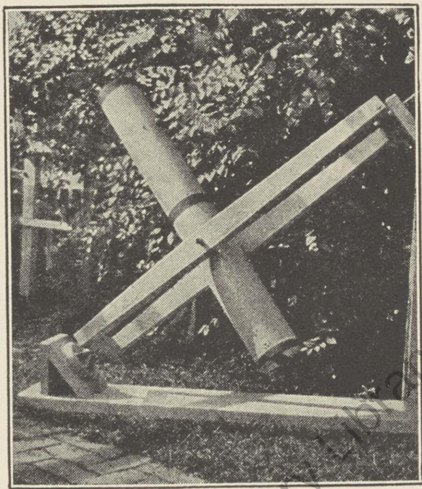
"Based on a great deal of experience in the grinding and polishing of still harder materials than quartz (gem minerals for scientific instruments, etc.—Ed.) I doubt if there would be any great difficulty in grinding and polishing quartz, using most any type of reasonably hard material. During the final grinding stages I think it is only necessary that the material be of such a nature as not to charge with the abrasive compound unless a material so soft as to be almost a polishing lap be used, in which case the charging is not serious inasmuch as the grains will all come to one level very quickly."

John C. Lee writes as follows: "My quartz mirror was ground on a lead lap. The lap was fashioned on a lathe to the desired curvature and then grooved so that it looked like a conventional pitch lap (see page 149). The surface of the lap seemed to wear away very slightly as the grinding proceeded, and only enough to improve it."

Pyrex: Next to quartz in low expansion and contraction qualities comes Pyrex, having about 6 times the linear expansion of quartz but still only one-third that of plate and optical glass. This explains why the familiar Pyrex baking ware does not break when suddenly cooled on the surface; common glass contracts so rapidly on the outside surface when chilled that the stresses set up are too great for it and it fractures. Pyrex is a borosilicate glass containing boric acid and is manufactured by the Corning Glass Works. Quite a number of Pyrex disks have been supplied to astronomical observatories and physical laboratories, and they are available up to 12 inches in diameter. The cost is intermediate between that of plate and fused quartz. As is the case with quartz disks, the exterior of Pyrex disks is not smooth and the worker will be forced to make the most of what he can obtain, although this will have no real optical effect (which is about all that really counts). It is impossible to eliminate all bubbles and striae, but this has not prevented the use of the material among professional astronomers. If any bubbles happen to lie at the surface level they must be reamed out before work is begun, else they will chip and make trouble. Among the most perfect optical flats ever made are those at the U. S. Bureau of Standards, made by John Clacey, of quartz. These had bubbles which had to be reamed out in this fashion. (These

flats, by the way, each about 10 inches in diameter, were worked to one 200th of a fringe, or one 5,000,000th of an inch. Here is a star for the amateur to hitch his wagon to!)

Glass Mirror Substitutes: Although the beginner will wisely choose plate glass, and the average amateur will stick to it, there are a number of other materials which may be regarded as possible substitutes. Some still require more research, some are a demonstrated "wash-out" and others, like quartz, are a grand success but are not at present as available as one could wish.



A HOME MADE TELESCOPE

Made by Earl O. Graff and described in the Scientific American, September, 1927, page 281. This type is described in Part I, Chapter 2; see especially Figure 25. A. W. Everest made a mounting of the same double-forked type and devised a simple braking or holding device which proved ideal. A discarded baby carriage wheel with rubber tire removed was applied to either axis. In the groove of these wheels the brakes, consisting simply of strips of wood, one on either side of each wheel, and held lightly against the wheels by means of spiral springs, were allowed to run. This held the tube wherever placed, yet permitted easy motion.

Since many of the advanced amateurs will ultimately be likely to consider trying these substitutes and may have difficulty obtaining authentic information concerning them, they are described below. These descriptions are purposely inserted in some cases in order to call attention to the drawbacks of certain of them. This may possibly forestall futile efforts. Nevertheless, the resource-

ful amateur who loves to explore the byways is as likely as anyone to hit on some invaluable discovery, hence the consideration of the various materials is encouraged. Dr. F. G. Pease of Mt. Wilson Observatory, in canvasing possible substitutes for glass for very large reflecting telescopes, makes the following statements (in *Publications of the Astronomical Society of the Pacific,* August, 1926):

"Another method early proposed was to quarry a block of obsidian and fashion it into a mirror. Obsidian is a volcanic product occurring in large masses, usually fractured into small pieces; but Dr. F. E. Wright of the Geophysical Laboratory informs me there is a ridge in Iceland, from which blocks could be cut far larger than would be required for a 25-foot disk. Obsidian is easily ground and polished, and silvers well. It contains, however, quantities of fibrous and crystalline material which cause defects in the polished surface.

"It has been proposed to build mirrors of concrete or cement and face them with silver. It is almost certain that such mirrors would be failures for the class of instrument which we are discussing. Concrete changes its form as it ages and no amount of grinding can remove its surface grain. With a coating of silver thick enough to cover this grain and permit a uniform surface, the differential expansion of the silver and the concrete would cause large distortions of figure, and the chances are the silver would buckle or peel.

"Various marbles, resins, waxes and grainless cements have been tried as mirrors, but fault can be found with all of them when considered from the standpoint of a large, permanent, precision mirror.

"Attempts have been made to coat various materials with alloys or metals by spraying with an air gun. Microscopic examination shows that such surfaces are grained and fibrous, and unfitted for fine astronomical purposes.

"There is a promising field for research in the investigation of metal alloys suitable for mirrors. When one considers the enormous number of possible combinations of metals, he has hopes of finding an alloy which would be light in weight, which could be cast either solid or as a ribbed plate, and which could be easily silvered, if not in itself possessing excellent permanent reflecting properties.

"Alloys are known which possess some of these desirable properties, and it may be that the addition of other metals, or new combinations of them, would yield the desired material.

"Metals very quickly adjust themselves to variations in temperature, and, consequently, would have a good figure most of the time. Their coefficient of expansion is large, but this property is not inherent in all alloys.

"Invar, for example, is an alloy of 64 per cent steel and 36 per cent nickel, which has a coefficient of expansion practically equal to zero. Its reflecting power is not high, but it can be silvered. If it were possible to cast a large ribbed plate of *Invar,* or to build up a mirror from sheets and separators, it might serve our purpose.

"Speculum Metal is a bronze composed of 68 parts of copper and 32 parts of tin. Most of the early reflectors, including the 6-foot mirror of Lord Rosse,

were made of this material. Its reflecting power gradually drops from 70 per cent in the red to 50 per cent in the violet. It tarnishes in the open air and must be repolished and figured in the optical shop.

"Stellite has been used for mirrors in small sizes. Its reflecting power varies from 64 per cent at 6500 to 54 per cent at 4000. (6500 refers to wavelength in Angstrom units and would be in the red; 4000 would be in the violet.—Ed.)

"Magnalium mirrors made of 31 parts of magnesium and 69 parts of aluminum, possess a reflecting power of about 83 per cent in the visual region, which gradually drops to 67 per cent at 2510 (in the ultra-violet.—Ed.). Early mirrors made of this material were poor, but the art of casting aluminum alloys has since improved greatly and it is possible that good light castings could be made today.

"Stainless Steel Mirrors containing 11 to 14 per cent chromium, now enjoy considerable use in small sizes and possess the advantage of retaining their brightness over long periods of time under circumstances which would ruin a silver coating. Measurements of their reflecting power yield values from 60 to 80 per cent in the visual region of the spectrum. The coefficient of expansion is higher than that of steel.

"The alloy which the astronomer looks forward to might be called 'Mirrorite,' and the time may arrive when metallurgists, by careful research, will so combine metals as to produce this remarkable material, having the reflecting power of silver, the zero coefficient of expansion of *Invar*, the freedom from tarnishing of stainless steel, and the lightness of magnalium.

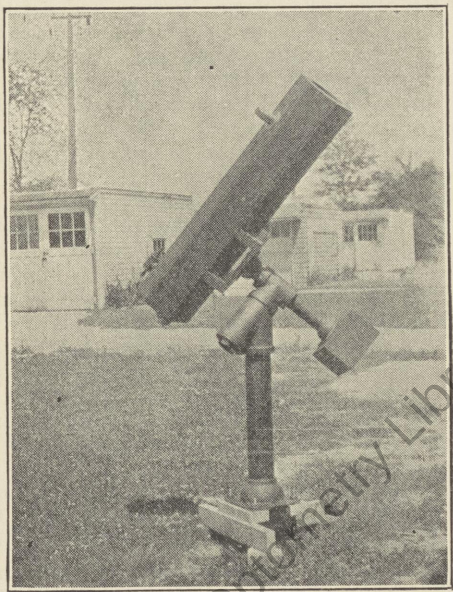
"Telescopes have been proposed in which many independent paraboloidal mirrors all point to the same spot. The mechanical mounting of such a system of mirrors would not be difficult to build. The light-gathering power of such a telescope would equal the sum of that gathered by the individual mirrors, but the resolving power would be only that of a single mirror. Owing to the fact that most of the mirrors would be used in oblique positions, the quality of the image would be poor.

"The construction of a large mirror composed of separate pieces, whose surfaces are parts of a single paraboloid would be more difficult to make than a single disk. To grind and polish the parts simultaneously would require a large solid backing. To grind and polish each part individually would involve an enormous amount of 'local' work. The resolution of such a compound mirror would equal that of a single mirror of the same aperture, provided the pieces were in the shape of sectors whose adjoining edges were covered by the diaphragms supporting the secondary mirror. If many small pieces were used each image would be accompanied by surrounding spectra, just as though the mirror were covered with a grating."

Obsidian or volcanic glass is usually black. The Editor purchased a chunk of this mineral, obtained originally in Utah, from Ward's Natural Science Establishment, and Porter sawed out of it a 2½-inch disk, ground it, polished it and figured it. He states that "it sliced as readily as glass. The only difference I could note between working obsidian and plate glass," he con-

tinues, "was that the obsidian would not take quite so fine ground a surface as that of glass, and a little longer time was correspondingly required in polishing. The resulting surface was a lustrous black, giving an admirable background for showing Newton's rings by ordinary daylight, when brought into contact with a glass flat." Obsidian in some cases is pure glass, in others a mixture of glass and crystals, depending on original rate of cooling from lava.

Invar, an alloy used for tapes, etc., because altered but little by temperature and having the smallest coefficient of expansion known, has been tried



A HOME MADE TELESCOPE

The mirror is a 6 inch. The mounting is built around heavy standard pipe fittings, yet they are none too rugged. Many telescopes are mounted too lightly and thus are anything but rigid. It is hard to overdo the matter of rigidness. This telescope was made by Sheldon K. Towson and was described in the Scientific American, August, 1928, page 172.

out by at least one amateur, G. H. Lutz. He has devoted years to research on various alloys regarded as mirror candidates, and has made seven mirrors of *Invar.* He states that, in common with all alloys that he has tried, it reveals its crystalline structure when polished, the crystals of the softer ingredients not behaving the same as the harder parts. *Invar* is a copyrighted name;

some refer to this alloy as "36 per cent nickel-steel" or "thermostatic nickel-steel." The alloy is made by the Crucible Steel Company of America; the Holcomb Steel Co.; and the Simonds Saw and Steel Co. The finished *Invar* mirror must be plated to prevent tarnish, and, says Lutz, "the plating has its own problems that call for a lot of patience. Chromium and many other materials have been made use of for plating, and the end is not yet. I am still experimenting."

Stellite was tried by Lutz on several mirrors, one of which, a $10\frac{1}{2}$-inch, he showed to The Editor. He says it cost him many hours to master, as the outstanding quality of this alloy is its extreme hardness and resistance to abrasion (also corrosion). This is why it is used for high-speed machine tools, knives, oil well tools, dredge dipper cutting edges, etc. The relative resistance to abrasion of Haynes Stellite is 4 to 9 times that of steel. Lutz states that he used up 8 inches of brass tubing and 4 pounds of carbo. in drilling a $1\frac{3}{4}$-inch hole through his mirror, made of this remarkably hard alloy, and, he writes, "I will not wantonly advise anyone to start to make a mirror from *Stellite,* as I do not wish to make any enemies. However, if one has a machine, plenty of time and unlimited patience there is a chance." The alloy, which is said to be one of chromium, cobalt and tungsten, is not cheap. Lutz had trouble due to the crystals of tungsten remaining above the surface, but the later results were gratifying when he obtained a form of the *Stellite* in which the tungsten was reduced to the lowest possible limit. He did not have to pay any attention to temperature while working it, the figure not being thus affected; cold water could be run on the hot mirror (this is also true of *Invar*). Air temperature changes during observation did not alter the figure, as with glass. The coefficient of expansion is about half again that of glass, but heat is conducted very much more quickly through all metals, hence the point is largely academic. The manufacturer states that *Haynes Stellite* reflects from 83 per cent of the incident light in the red to 68 per cent in the violet.

Stainless steel mirrors are made by W. Ottway and Co., Ltd., London, but not in paraboloidal surfaces. Ernest Brookings, metallurgist, Jones and Lamson Machine Co., has made recent experiments with chrome steel for mirrors.

Copper, electrolytically deposited, reflects 48 per cent in the blue to 90 in the red; commercially pure copper, 32 and 83, respectively. *Gold,* electrolytically deposited, 29 and 92. *Silver,* 86 and 95 (when untarnished, of course). Figures given are from the *Smithsonian Physical Tables* and are for perpendicular incidence and reflexion.

Rotating, Mercury Mirror: Dr. R. W. Wood, Professor of Experimental Physics at Johns Hopkins University, attempted in 1908 to make an automatically paraboloidal mirror of variable focal length by the theoretically practicable method of rotating on a central, vertical axis a round, shallow pan of mercury. Under centrifugal action the mercury takes on the figure of a true paraboloid. Using a 20-inch pan, a rubber thread transmission and a magnetic clutch, Dr. Wood obtained interesting results, the focal length being varied with ease by changing the speed. Minute irregular disturbances injured the perfection of the mirror's surface, despite the velvety transmission or drive.

The mirror was rotated at the bottom of a well, and since it is horizontal, it reflected only the zenith stars; a flat would therefore be required to complete the equipment so that it would take in a large field. The original experiments were described by Dr. Wood in the *Scientific American,* March 27, 1909, page 240 (out of print—consult at large public libraries), and in *Astrophysical Journal,* March, 1909. This interesting experiment was originally proposed in the *Scientific American,* Dec. 13, 1873, page 368, by someone who signed "D." It is known, however, that "D" was David Todd, later to become Professor of Astronomy at Amherst College. Dr. Wood's experiment was not completed. The elimination of the ripples required a *constant* speed of drive.

The above note was submitted to Dr. Wood with a request for comment. He replied as follows: "The experiments were continued after the publication of the papers, but I never published anything more on it. I got it to work much better the second summer. I put a 20-inch flat over it and had excellent views of the Moon. The final conclusion was that constant speed of drive would eliminate the slight tidal wave, which was all that remained. I did not even have a synchronous motor. One of these, operated on a modern A.C. circuit with the cycle frequency controlled by clock, would be a great improvement. I do not advise anyone to try the mercury mirror, however."

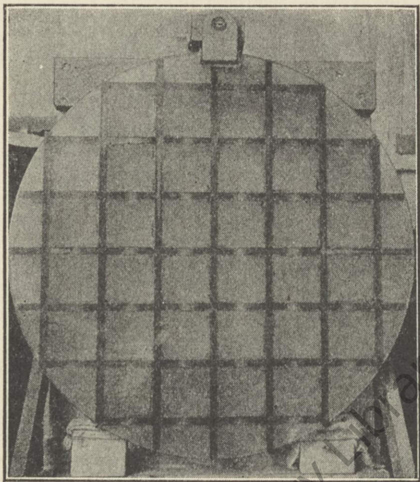
The synchronous motor referred to above involves an interesting development for the amateur who may have planned to make a mechanical or conventional type of clock drive. Instead, let him ascertain whether his local alternating current is clock-controlled at the central station, and if so, consider a motor drive. As F. M. Hicks states it, "Where the local electric current is constant one can drive with a constant speed motor (that has been synchronized at a small cost) and it will cost only a fraction of the price of a good clock, and still be good, say, for photographing where exposures are wanted of two or three hours' duration." B. W. St. Clair states that "with the average central station it is quite easy for anyone to make an electric clock that will drive an ordinary telescope quite satisfactorily. Most of the large central station systems are controlled by a clock of astronomical type, which results in very fine time-keeping properties for any piece of equipment that is driven by a synchronous motor. I believe that it is feasible to build such a driving clock, using, say, a 0.01-H.P. synchronous motor and reduction gears such as can be bought on the open market."

Cellular Mirror: Professor George Willis Ritchey, who figured the 60-inch and 100-inch mirrors at Mt. Wilson Observatory, and also the 24-inch reflector mirrors at Yerkes, has recently been working on a new cellular type of glass disks for optical mirrors of large telescopes. Each mirror disk of the new type consists of a front and a back circular glass plate, with a deep rib system also made of glass plates, between, and separating, the two. For mirrors from 60 inches in diameter up to the largest sizes ever considered the glass plates are all about one inch thick. They are made by the celebrated St. Gobain Glass Company, of a special, low-expansion glass perfected for this purpose. All plates for a given mirror are carefully selected for uniformity of thickness, of coefficient of expansion, and of flexure index.

The various plates are fitted together by fine grinding, and are then

cemented together with a thin layer of Bakelite cement much less than one micron [practically 1/25,000 inch.—Ed.] in thickness, thus forming a comparatively light and very rigid cellular structure. For a concave or a convex optical mirror the front glass plate is curved to the proper degree, but is of *uniform thickness* throughout, and is of the *same* thickness as all other plates composing the cellular disk.

In order to permit the air to circulate freely within the multi-partitioned interior round holes are cut through the sides of each rib or partition. A posi-



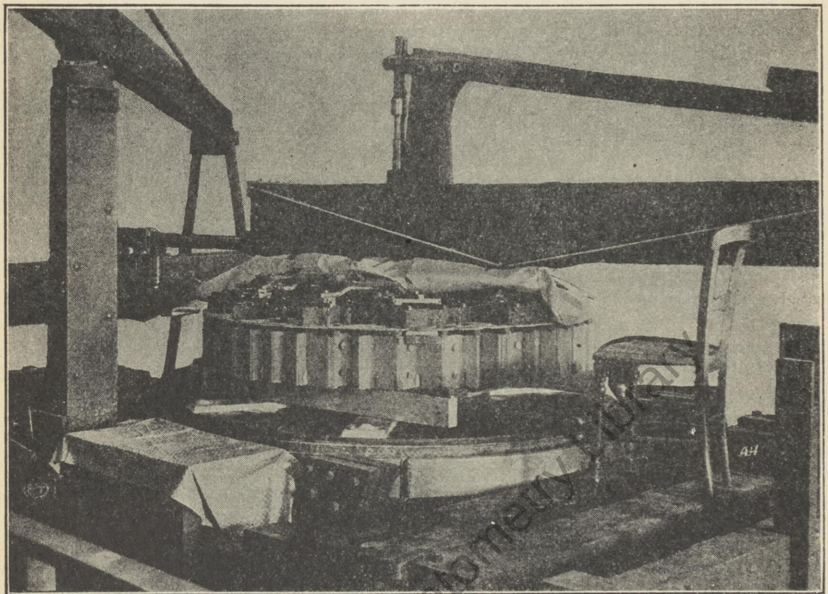
RITCHEY CELLULAR MIRROR

The whole structure, a 30 inch flat, is propped up on edge. The dark grid is the partition work of ribs and plates seen edgewise and through the thin mirror disk itself. The evenly spaced ventilating holes in the ribs may clearly be made out. Professor Ritchey states (Journal Royal Ast. Soc. Canada, July-August, 1928) that this mirror "has retained its optical figure for three years without change which can be detected by the most sensitive optical tests."

tive or forced circulation of air is used. Thus, adaptation to temperature changes takes place rapidly, especially as no glass thicker than an inch enters into the structure. The whole mirror has only one-fifth the weight of a solid disk, and holds its figure so perfectly under widely varied working conditions that no change of form can be detected with the most sensitive optical tests. For descriptions, see *L'Astronomie,* Feb., 1926; *L'Illustration,* April 24, 1926; *La Science et La Vie,* August, 1926; *Popular Astronomy,* May 27, 1927, p. 258.

Thus far Professor Ritchey has made mirrors of this kind (cellular) up to 60 inches in diameter which, he states, have remained optically plane under temperature changes such as those which occur in the open dome at night.

In a communication to The Editor, Professor Ritchey writes from *l'Observatoire de Paris,* where he is conducting many of his researches: "I am also developing two new types of photographic telescopes—the Schwarzschild and the Ritchey-Chrétien. The first of these has a large concave and a small concave (secondary) mirror; the second has a large concave and a small convex



RITCHEY CELLULAR MIRROR

The ribs and plates show plainly. This is Ritchey's second cellular experiment and is a concave mirror about 60 inches (1.50 meters) in diameter. Made in 1925-1926.

(secondary) mirror. Both have *new curves* of the mirror surfaces (other than paraboloid and hyperboloid). Both give much larger fields and much smaller, more concentrated, images of out-of-axis stars, than the paraboloid gives.

"The Ritchey-Chrétien type allows the shortest tube and smallest dome of any reflecting telescope type, about one-half those required for the type of the 60-inch and 100-inch at Mt. Wilson. The out-of-axis images are so small, round and concentrated that, on an average, for a field of 40 minutes of arc diameter, we will photograph out-of-axis stars which are at least two magni-

tudes fainter than those photographed with a Newtonian of equal aperture and focal ratio.

"This is a revolutionary result, and has been fully demonstrated in this laboratory. These small images demand refinements of guiding and focusing, of convenience and consequent efficiency of the observer, and of protection of the telescope mounting and tube from temperature changes and from flexure, *far beyond those attained at Mt. Wilson by the writer;* these refinements have all been fully worked out in this laboratory.

"The Schwarzschild type also gives a very large field of small, round images, together with very small focal ratio—as short as 2½ or 3 to 1—so that the light concentration for nebulae and faint stars is very great. But it is a most inconvenient type in use, unless it be used as a fixed telescope with a coelostat. When so used it becomes as important and revolutionary as the Ritchey-Chrétien. The two new tyes of mirror curves, used interchangeably, with various focal ratios, in conjunction with the fixed, universal telescope; together with the cellular, ventilated mirror disks made of extremely strong, rigid plates of low-expansion glass, will inaugurate a new epoch in telescope efficiency, in astronomical photography, and in accuracy of astronomical measurement."

These new conceptions are described in *L'Astronomie* in a series of six monthly articles beginning December, 1927; also in *Journal Royal Ast. Soc. Canada,* beginning with the May-June issue, 1928.

In the first article Professor Ritchey outlines his plans for a modern observatory with a great, vertical, fixed telescope having a coelostat and quickly interchangeable, cellular mirrors of the two new types, Schwarzschild and Ritchey-Chrétien.

Commenting on the first edition of *Amateur Telescope Making,* Professor Ritchey writes: "I am *most* heartily in sympathy with your efforts in regard to amateur optical work such as you describe in the little book which you so kindly sent me. Henry Draper's remark that 'the future hopes of astronomy lie in the multitude of observers, and in the concentration of action of many minds' is true. The greatest single need of astronomy today is the thorough popularization of it. This is easily possible by means of the finest attainable astronomical photographs. Astronomy could have, and soon *will have,* a thousand devoted friends assisting in every way in its development, where it now has one such friend."

The amateur should read well Ellison's comment on page 73. The professional, he points out, has nearly always started as an amateur. No professional has risen to higher attainments than Professor Ritchey.

Suction Mirror: Another unusual but possibly worth-while effort would be the conversion of a flat mirror into a paraboloid by atmospheric pressure. By producing a partial and variable vacuum behind the mirror the latter will be caused to sag inward and the curve should theoretically be a paraboloid. One worker is known to be experimenting with this method at present, while Porter states that he tried it out in a preliminary way in 1910, getting far enough with it to conclude that it was worth further effort.

Magnesium Oxychloride Mirror: This was described by F. Le Coultre in

Bulletin de la Société Astronomique de France, 1925, page 484; see also *Zeitscriften für Instrumentkunde,* 1926, page 588. The following is an abstract published in *Journal of the Society of Glass Technology.* "Several attempts were made to find a satisfactory substitute for glass for large telescope mirrors. The most successful results were obtained by mixing 100 parts of magnesium oxide with 24 parts of a one-half per cent aqueous solution of magnesium chloride which, on being thoroughly mixed, set readily into a hard, white mass. For the production of a concave mirror, the viscous mixture was poured into a mould, which was slowly rotated until the mixture became stiff. The

Science Service Photo.

PROFESSOR GEORGE WILLIS RITCHEY

From a photograph taken in his optical laboratory at the Paris Observatory, by James Stokley, 1927.

surface was then polished by means of emery and rouge. This mixture was not impervious to water, and it had the further disadvantage that it was attacked by CO_2, and the surface when silvered was not so good as a silvered glass surface. To overcome these defects the surface to be silvered was dipped into a 40 per cent solution of formalin. Afterwards the block was immersed, with its reflecting surface upwards, in a 2 per cent silver nitrate solution saturated with formalin, when the magnesium oxychloride immediately became covered with a brown deposit of silver oxide. The mirror was then taken from

the bath and dried. The surface became black through the decomposition of the protoxide into sesquoxide and metallic silver. When it was quite dry the mirror was polished with rouge. The finely divided sesquoxide was rubbed off and the metallic silver formed a layer on the surface, as hard and as highly reflecting as if on a glass surface."

While glass is still king, after many attempts to discover a better material, this does not prove that nothing better will ever be found. And amateur experimenters are as likely to make a valuable discovery as professionals.

Coefficients of Expansion and Relative Thermal Conductivities, both of which are likely to prove useful to the telescope maker, are quoted below, from the Smithsonian Physical Tables. These are for degrees Centigrade.

	Expansion	*Conductivity, Heat*
Plate glass	.00000891	
Crown glass	.00000954	.003
Flint glass	.00000788	.0018
Quartz, fused	.00000057	.0023
Speculum metal	.00001933	
Cast iron	.00001061	
Steel	.00001322	.107
Silver	.00001921	1.006
Stellite No. 6, cast...........	.0000165	
Stellite No. 6, forged..........	.0000146	
Invar	.000000374 to .00000044	(Bureau of Standards)
Stainless (chromium) iron.....	.0000010	(Bureau of Standards)

The decimal fractions quoted relate to that portion of the total dimension of the piece of material used, which the material will be increased or decreased by each increase or decrease, respectively, of 1 degree, Centigrade, in temperature. A degree Centigrade is equal to 1.8 of a degree, Fahrenheit.

Eyepieces: The principal types of eyepieces are the positive or Ramsden and the negative or Huyghenian. Both types contain an eye lens and a field lens, each of which is plano-convex. In the positive or Ramsden eyepiece these convexities both face the same way—away from the eye; the focal plane lies just in front of the field lens; hence this type may be used as a low-power magnifying glass. In the negative or Huygens eyepiece the convexities face each other; the focal plane of the negative lies between the lenses. Therefore it cannot be employed as a common magnifying glass. This is the easiest way to distinguish the two types.

Which type is the better? Reams of words have been written on both sides of this argument which never will be settled, because both types have their points. The positive has the larger field and less color, but dust on the field lens shows up prominently when the telescope is in use. The negative is the older type—much older, in fact.

Many prefer the positive, Hastings, three-lens type.

Then there is the so-called "erecting eyepiece" for terrestrial telescopes, to use when it is awkard to see things upside down. This consists of two plano-convex lenses with convex sides toward the eye, and still nearer the eye, two

bi-convex lenses. It erects the image, but its added lenses absorb and reflect a certain amount of light. A way to get around the lack of an erecting eyepiece is to face the object to be seen telescopically, get it into the field of view (inverted, of course), then turn one's back to it, thus inverting the eye itself so that the object is seen erect again.

A good diagram of an erecting eyepiece is shown in Todd's *New Astronomy.* Surveyors' transits are not equipped with erecting eyepieces, yet it is surprising to discover how soon one educates one's eye to see things well through them; even though seeing upside down. Numerous modern modifications of the basic types of eyepieces are described in Bell, *The Telescope.*

Old microscope eyepieces are suitable for use in a telescope, though they are usually the Huyghens type and give only a narrow field. If one will regard the eyepiece simply as a local magnifying glass for enlarging an image already formed by the mirror or objective lens of the telescope, just as if it were being used to magnify a tangible object, the real significance of the eyepiece of a telescope will be clear. This will also explain why eyepieces of different powers may be used with the same telescope.

A telescope is essentially (1) a big "eye" for gathering light (the human eye opening or iris is also a light gatherer, but it is only one-third of an inch in diameter); (2) a properly curved instrument for bringing this light to a focus; and (3) a separate microscope for remagnifying it locally.

Grinding: The nature of the grinding operation is not generally believed to be the more obvious one. Without taking particular thought one might assume that the grains of abrasive act simply as plows, like the tool on a planer or shaper. It is thought, however, that this sort of thing occurs only when a grain drops into a depression in the one glass disk or the other and becomes lodged there. Mainly, the operation of grinding is something like what we would have on a large scale (visible) if we were to place a number of large steel balls on a cake of ice, with a second cake on top of the balls, and move the upper cake over the lower. Behind each ball, as it rolled, there would be a path, not planed or gouged out but *fragmented by pressure.* On glass we get something of the same thing with a glass cutter, which is not a cutter at all, but a local splinterer. With abrasives, the pressure directly under the particles is transferred downward and outward, and conchoidal chips of glass are pushed and sheared out laterally. And the greater the pressure the greater the depth of shearing involved. Grinding takes place in direct ratio to pressure per unit area, a point which answers the frequent query "How hard should I bear down?" The answer is: "Do you feel stronger than you feel patient, or more patient than you feel strong?"

Polishing, theory: "The process by which a ground or smoothed surface is turned into a polished one has been the matter of a good deal of debate," says F. W. Preston in *Glass Industry,* (Feb., 1928). "Some contend that the ground surface is liquefied by the drag of the polisher and, as it were, smeared about like butter on bread. Others contend that polishing is really just an exceedingly fine grinding operation."

Amateurs who are of a more or less investigative turn of mind and who

have access to a large city or university library will find in the files of the *Transactions of the Optical Society* (London) some interesting food for thought on this much-debated question. Exactly what actually takes place during the polishing operation? Is it simply a case of ordinary abrasion on a finer scale, or is it something else—perhaps molecular flow? Discussions of this question are to be found in several of the earlier numbers of the journal mentioned, most of which The Editor found to be available from the Optical Society. These journals came rather high, averaging about two dollars an issue, with a 25 per cent duty to pay the postmaster at this end. However, if one wishes to obtain them, inquiry should first be made direct to London, regarding the availability and price, postpaid, of each individual issue, for the prices are not uniform. Most readers will, however, be satisfied with a summary of these several theories of polish, which is quoted from a lecture by Dr. L. C. Martin of the Imperial College of Science and Technology and which was published in the *Journal of the Royal Society of Arts,* August 12 and 19, 1927, under the title "Recent Progress in Optics." The Editor has taken the liberty to insert in Dr. Martin's statement, within parentheses, the exact references to the *Transactions* wherever he mentions papers previously published in them.

"In 1907 G. J. Beilby described researches on the nature of the polishing process (*Transactions Opt. Soc.,* Volume 9, 1907, page 22); he distinguished this as very different from grinding. Herschel had believed that the final polishing was merely a very fine grinding, the direct continuation of the process by which, using finer and finer grades of emery, the outstanding irregularities of a surface are worn away by the actual removal of material. Beilby showed, however, more especially with regard to the polishing of speculum metal, that the polishing action consisted, in part, of a flowing action which would cover over the irregularities of the surface. The skin of the material, he concluded, owed its nature and stability in all cases to the surface tension, a conclusion markedly different from that of Lord Rayleigh, whose view in 1901 was that the polishing of glass consisted in an almost molecular wearing away of the highest parts of the surface, and who had supported this view by proving that a thickness of glass equivalent to six wavelengths of light (about 1/10,000 inch. —Ed.) was removed during the polishing, as distinct from the fine grinding process.

"J. W. French, writing in 1916 (*Transactions Opt. Soc.,* Vol. 17, page 24), suggested that the surface layer of a polished piece of glass consisted of a portion which had been caused to flow, more or less, under the strong surface forces of the polishing operation. This layer, which he termed the 'Beta layer,' was considered, from evidence based on the study of fire cracks, to be about eight wavelengths deep.

"In more recent work by the British Scientific Research Association the depth of the deepest pits in a finely ground surface was examined microscopically. The results showed that irregularities of the order of six to eight wavelengths or more are present in such surfaces, thus indicating again that polish is only complete when the surface is removed to the depth of these deepest pits, when Lord Rayleigh's observation is borne in mind.

"F. W. Preston, in 1921 (*Transactions Opt. Soc.,* Vol. 23, page 141), ex-

pressed the view that the surface of finely ground glass is of the nature of a 'flaw-and-fissure complex'; in other words, the surface skin is a layer of finely 'cracked' material. The polishing action would then consist in the removal of the fissure complex. In such a 'grey' surface there are probably (so it is suggested) a certain proportion of fine cracks slightly wedged open by the displacement of parts of the material. This is a possible cause of the strain first observed by Twyman (*Proceedings of the Optical Convention of 1905,* page 78—same address as Opt. Society; this is a book, not a periodical.—Ed.). The action of polishing allows these fissures to close up; when their width becomes much smaller than a wavelength of light they cease to be visible."

In contradistinction to the various molecular flow theories of the majority of British theorists, Dr. Elihu Thomson states below his theory of the nature of the polishing operation. Dr. Thomson is Director of the Thomson Research Laboratory of the General Electric Company at Lynn, Mass., where fused quartz was developed and is made; he has been an amateur worker in glass for 60 years, has also made optical surfaces of diamond, and has made objective lenses up to 10 inches in diameter. His theory is reprinted, by permission, from *the Journal of the Optical Society of America and Review of Scientific Instruments,* Vol. 6, No. 8, October, 1922. He states:

"The problem of how it is that, for example, a glass surface which has been smoothed or finely ground can, by proper means, be polished not only so as to be invisible ordinarily, but so that under the severest tests it shows no diffusion of light (as of the sun's rays falling on it) has at times engaged the attention of the ablest physicists. The late Lord Rayleigh studied the matter and his paper (Lord Rayleigh, *Proc. Roy. Inst. Gr. Britain,* March, 1901; *Trans. Opt. Soc.,* 19, Oct. 1917) on the subject is well known. He properly explains the polishing process on the principle of removal, by a process similar to grinding, of the high points of the surface, and progressively so until the whole ground surface has been cut away, but the cutting is by an action so fine that the grain produced is beyond the power of resolution by a microscope or other powerful optical means.

"It is the purpose here to show that while this view is measurably correct it does not go far enough, and that the polishing is a unique mechanical process; a self-regulated planing down of the surface to a real level without even the finest scratches or other character which would lead to diffusion of any light falling on the surface.

"Some have most erroneously tried to explain the result of the process, by assuming that the glass has, during the polishing, actually flowed; or that there was some peculiar plastic condition brought about which allowed the glass surface being polished to take on the characteristics of a liquid surface. There is no need for such hypotheses and no validity in such assumptions. This will be made clear.

"In burnishing of plastic metals by a hard burnisher there is, of course, such flow, but with hard, brittle, non-malleable materials like glass the process is decidely not like burnishing.

"Glass may receive an optical polish in either the wet or dry way. Other

materials of a brittle, non-malleable nature are dealt with similarly; such are quartz, agate, calcspar (Iceland), and many jewels and minerals.

"In the manufacture of plate glass the ground surfaces (the last, or smoothing stage, being often called *mud ground*) are not worked by grinding to so fine a grain of surface as in the better class of accurate optical work, and the polishing is done by runners of felt charged with rouge (crocus) and water moved over the plate by machinery. The result is that the surface obtained is not an optical one; it has a smoothness and polish similar thereto, but is wavy throughout, as can easily be discerned by a skilled eye in regarding the reflection of an edge from such surface; and, of course, by other simple tests. It is neither optical in the large or small elements of surface. The yielding felt runners have swept out indiscriminately the hollows, small and large, and have not held the surface to a definite figure. Similar yielding polishers are used in finishing the very irregular surfaces of cut glass. The cheaper kind of lenses, where accuracy of figure is not needed, are often cloth polished, a process which, if carefully conducted, gives a result intermediate between the plate glass surface and the true optical surface, such as is obtained by a pitch polisher with rouge and water. The considerations as to the true nature, the mechanics, of the polishing process are applicable to all such cases, but will be given in connection with the pitch polishing, most usual in good work. They apply, too, to the case of dry or paper polishing with paper-faced tools charged with tripoli (diatomaceous earth), a method of polishing which has been used to some extent in France for medium grade lenses.

"In rouge polishing with pitch for a carrier, as is usual, the surface of the pitch is moulded to fit the glass and is divided (usually) into small square facets by grooving. It is worked over the glass, or the glass worked upon it, by movement in all directions or such innumerable paths are given that no definite course is repeated. This is essential to the best result.

"The conditions as found, in successful work, are as follows: The rouge, though very hard, is friable and breaks down to a very fine powder. Too hard (non-friable) rouge will tend to fine scratches. These scratches are not like grinding or crushing, but are smooth-bottomed grooves, discoverable by a magnifier.

"The pitch is at all times yielding. It is made so by tempering and testing. If too hard, it tends to cause fine scratches all over the surface which is being polished. These, with very hard pitch, may resemble grinding, but ordinarily they show no crushing, but are smooth cuts.

"In grinding, on the contrary, the surface is crushed, while in polishing it is clean cut. Smooth cutting is the rule. The polishing is indeed a kind of planing process; the particles of rouge set themselves into the pitch surface and cut smoothly; they do not roll or grind. There are millions of fine planing or cutting edges at work fixed in position by becoming, at least temporarily, embedded in the pitch surface, which readily yields to receive them. They make smooth cuts as can readily be seen by examination of the scratches when the pitch is overhard or the rouge too hard and non-friable. Good rouge is friable without apparent limit, and rouge washed out of a used polisher may be so fine as to float for days in colloidal solution.

"All the above considerations are fairly well known and recognized, but there is one additional condition or circumstance which, so far as the author knows, is worthy of record, no attention having been hitherto drawn to it.

"It is this: by the very nature of the case the particles which are doing the cutting in polishing are all *automatically adjusted,* in successful work, to cut to the *same depth* during any stroke. The yielding nature of the pitch surface not only ensures this, but makes it a necessary consequence, for any particle of rouge riding higher than another is at once depressed to the proper level by sinking into the pitch surface. The innumerable cutting edges of all the particles reach a common level, and with motion of the polisher in all directions, and cutting smooth (no crushing or grinding) the result cannot fail to be what it is, an optical surface without grain or irregularity. The rouge is friable without limit, so that the polishing particles may, in the process, become finer and finer. With felt, cloth or paper as a carrier for the polishing powder, the effect is much the same; the particles are held to position when cutting, as planing tools. Even fine washed carborundum will polish glass if held in the surface of soft wood or cork, and the author has even produced a fair polish on a glass lens by a soft metal tool charged with fine carborundum. In such case, the polishing takes place in a few seconds, but the technical difficulties are very great. In dry polishing, a sheet of paper is pasted down on the surface of the polishing tool, and a special high-grade pure paper, rather heavy and uncalendered, is used. This is charged by gently rubbing its surface with a lump of fine tripoli selected for the purpose, the fine silicious skeletons composing which constitute the polishing powder. The first application to the smoothed surface, as of a lens, which surface has the fine grain usual in such a case, is to show innumerable fine scratches, criss-crossing in every direction. They are, however, smooth scratches. As the work goes on, the tripoli works down to finer and finer conditions, while the polishing comes up gradually, no new application of the powder being required after the start. It is manifest that here, too, is the condition of smooth cutting and particularly a self-adjustment of cutting depth, owing to the yielding character of the paper surface, so that at the end all the cutting is done in one surface of movement. It is believed that this dry paper process is much less used than formerly. It cannot be expected to yield the high accuracy that may be obtained with the wet pitch.

"It is thought that in pointing out the mechanics of the polishing process, and more especially the smooth cutting and self-adjustment of cutting particles above described, the interesting process of the production of an optical surface may be relieved of something of the mystery which has been its accompaniment.

"The author has drawn upon an experience of more than fifty years in occasional working of optical surfaces on glass of many kinds and on media, such as crystal quartz and fused quartz, Iceland spar and others.

"The amount of material removed from the surface under treatment is, of course, seen to be almost infinitesimally small per stroke, and it is only by the long continuance of this action that at last there is a sufficient removal to secure an optical surface. Time is saved by carrying the fine grinding or smoothing as far as possible before applying the polisher. As Rayleigh has

stated, and it is, of course, the common experience, polishing begins on the highest or most elevated parts of the surface, seen only under a magnifier, and these are removed while the polished spots widen out, and, if the surface has been well prepared, or *bottomed,* as it is termed, spread to include the whole surface. If the surface has not been well bottomed there will remain pits which the slow planing action of the polisher is incompetent to remove in reasonable time, and if the polishing is continued too long the surface is more than likely to have lost its truth, or has been seriously deformed. This, however, depends on the polisher itself keeping its form. Too soft pitch is a guard against polisher scratches from particles of grit, but not conducive to accuracy. Accuracy can be helped by remoulding the polisher at intervals by slight warming of its surface and application to a true surface of the same character as that being produced, while moistening the said surface to prevent adhesion.

"No matter what degree of smoothness has been attained in polishing, the continued smooth removal of the glass surface goes on as long as there is rouge, pitch and water applied; a fact which is, of course, taken advantage of in parabolizing a concave astronomical glass mirror."

In addition to the references to the back files of the *Transactions of the Optical Society,* quoted above, the scientifically inclined amateur will find valuable material in the same periodical, No. 1 of Volume 18 (1917), "More Notes on Glass Grinding and Polishing," by James Wier French; also in Volume 19 (1917), No. 1 (Oct.), "Polish," by Lord Rayleigh; and in No. 3 for 1925-26, pages 181-189, Preston on "Nature of the Polishing Operation." See letter in *Nature,* London, Sept. 4, 1926, page 339.

H. Dennis Taylor, of Taylor, Taylor and Hobson, Ltd., states in *Transactions of the Optical Society,* Volume 21, page 82, "If the rouge imbeds itself thoroughly in the pitch surface where it touches the glass, so that the said surface appears of a rich orange red, *not* glazy when dry, but of a matt surface, then we always know that both the polishing and figuring are going on satisfactorily. In hand polishing the sweetness and evenness of the frictional resistance is then most noticeable, whereas if the pitch surfaces in contact with the glass appear to be glazy in appearance when the polisher is dry, we know that the polishing and figuring are not going on satisfactorily; we then expect trouble and generally get it. In the case of hand polishing, a polisher in this condition is apt to suck and only move in jerks.

"Still worse is it when the pitch surface in contact with the glass refuses the rouge and shows a black, glazy appearance; then we usually get the glass covered with fine scrubs, while it refuses to take a good figure. This sort of polisher clings hard to the glass and can only be moved by hard jerks."

To The Editor, at least, this statement by Taylor would seem to bear out Dr. Elihu Thomson's theory of polish. While it is possible to polish an optical, glass surface on a pitch lap from which the rouge has been washed, an attempt to do this with a lap which has never been armed with rouge will possibly prove illuminating.

Transactions of the Optical Society, No. 3 for year 1922-23, contains an article on the properties of pitch, by F. W. Preston. The Editor has already made numerous references to the *Transactions,* which are not, however, mainly devoted to telescope making, as might logically be inferred from these references. The articles mentioned are the few of that nature which were found while going systematically through all the back files.

Herschel's Mirrors: In *Transactions Optical Society,* No. 4 for 1924-25, Dr. W. H. Steavenson, F. R. A. S., outlines a "Peep into Herschel's Workshop." Sir William Herschel left four complete volumes in manuscript, relating to his various processes and experiments, in which he sums up the results of 40 years of experience in the art of telescope making. These manuscripts are now in the hands of the Royal Astronomical Society, and, says Dr. Steavenson, "it is greatly to be desired that means should some day be found for publishing them." (Here is an opportunity for some generous amateur enthusiast or group of enthusiasts.—Editor.) The same issue describes and illustrates Herschel's many mirrors, eyepieces, etc., which are still in possession of his granddaughter, Miss Caroline Herschel. Herschel did not use the knife-edge test, because Foucault had not yet hit upon it. He worked by feeling and by a remarkable sense of intuition. Some of his mirrors had been soldered down in cans prior to his death in 1822. Opened in 1924, a century later, they were found to be splendidly polished and without a trace of tarnish! Most of them were found to be over-corrected and to have two or three zones, yet on the whole the figure of all the mirrors was up to a very fair standard, and it is probable, says Dr. Steavenson, that they performed quite well in actual use. The complete report is extremely interesting. Think of the thrill of opening up cans containing mirrors sealed up 102 years previously by Herschel and testing the work of this great master, for the first time, under the knife-edge!

First Announcement of Foucault Test: True devotees to the ancient and honorable art of telescope making may discover real interest—though no new information—in a holy pilgrimage to some large library to look up the first publication, in 1859, of information concerning the famous Foucault test with the knife-edge. They will find it in a long paper by Foucault himself, safely ensconced in Volume 5 of the *Annales de L'Observatoire Impérial de Paris,* pages 197 to 237, and entitled "Mémoire sur la Construction des Télescopes en Verre Argenté." Do not miss the incomparable engravings in the back of the volume, showing the characteristic shadow of ellipse and paraboloid and the theory of the test. After studying these engravings and reading Foucault's lucid account it will become evident that he did not rush into print until he had both theory and practice of the new test well worked out. A rather rare old book entitled *A Compleat System of Opticks,* Cambridge, England, 1738, by Robert Smith, describes on page 310 a test which is really the eyepiece test but which bears certain superficial resemblances to Foucault's test. The test was devised by John Hadley, inventor of the sextant. After reading Robert Smith's description of it, one is struck by the fact that Hadley, had he gone on experimenting, might have blundered on the knife-edge test 75 years before it was actually discovered by Foucault. How Herschel would have thanked him!

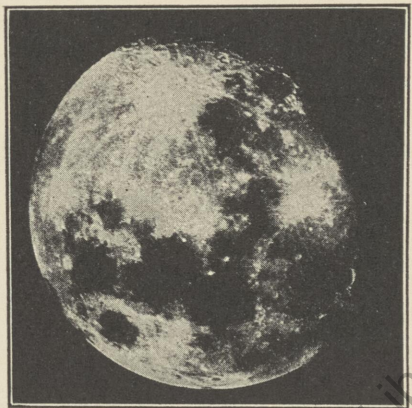
The Objective Lens: We have previously omitted from this book mention of objective lens making because we wish to confine our interest as far as possible to a single effort, the encouragement of reflecting telescope construction, rather than to attempt to spread over broader territory; also because in the average case the objective lens is not a very suitable work for the amateur—certainly not, at any rate, for the beginner. Some, however, who may have successfully completed several mirrors and who happen to be "born artists" (see page 89) may suceed at this job, though it is well to approach it with due humility unless one expects nothing better than a mediocre job. In making an objective lens there are four surfaces to figure instead of one, and attempting this job without first having made a few mirrors would be like attempting to do the "grapevine" before one had learned to stand up on skates. In a private communication Ellison writes: "There is no doubt that the making of an objective lens is a job to tax the abilities of the most expert. Yet, knowing what I do of your enterprising countrymen, I felt sure that, given the information, there would be a considerable number anxious to attempt the task, and that a certain proportion of these would attain to success." The literature on the subject is scarce. A brochure giving curves for a single type of lens (for a 1-inch finder telescope), previously calculated and ready to use, may be purchased from John M. Pierce, and a second brochure tells how to make a simple eyepiece. Specific instructions for computing the radii of an achromatic objective (5-inch) by Charles L. Woodside appeared in the *Scientific American Supplement,* Dec. 11, 1897. This is out of print, but can be found in library files. Condensed instructions by means of which the physicist may design his curves are contained in *Letter-Circular* 67, U. S. Bureau of Standards, Washington, D. C., gratis. A more abstruse theoretical discussion of the same nature appears in the *Transactions of the Optical Society* for May, 1919. Neither this nor the Bureau of Standards circular above mentioned gives practical instructions for proceeding with the actual work. *Popular Astronomy,* May, 1926, contains an article by Loren S. Noblitt giving brief, practical instructions. By far the best of all, however, is the original Ellison book treatise, now revised by the author and included in Part II of the present volume.

Astronomical Photography: Those who wish to try astronomical photography should obtain a little book called *Astronomical Photography for Amateurs,* by H. H. Waters. Professor Edward Skinner King of Harvard College Observatory states, as this edition goes to press, that he is preparing a small book called *Astronomical Photography,* to be published sometime later. Professor King suggests in his letter that The Editor mention the *Autobiography of John Brashear* as an incentive to amateur workers, particularly in view of Brashear's early struggles to produce his first mirror, his patience and his persistence. Brashear began as an amateur, found he could make good mirrors, advertised his work in the *Scientific American* (Oct. 30, 1880), and after a long career made the great 72-inch mirror of the Dominion Astrophysical Observatory at Vancouver, B. C. Returning to astronomical photography for amateurs, Latimer Wilson has done successful work of this kind, and has published two articles on it in *Popular Astronomy* (May, 1926; Aug.-Sept.,

1927). In *Popular Astronomy,* Jan., 1926, page 69, Robert Ellms of Baldwin-Wallace College tells how he took astronomical photographs with an ordinary Kodak, using film.

Harold A. Lower has taken some excellent lunar photographs with a 6-inch reflector, superspeed Eastman cut film and simple equipment.

In the *Journal of the British Astronomical Association,* Jan., 1928, F. J. Sellers, F. R. A. S., summarizes in three pages the work of lunar photography with small telescopes. He has done considerable research in that direction and the article contains in compact form the results of this research.

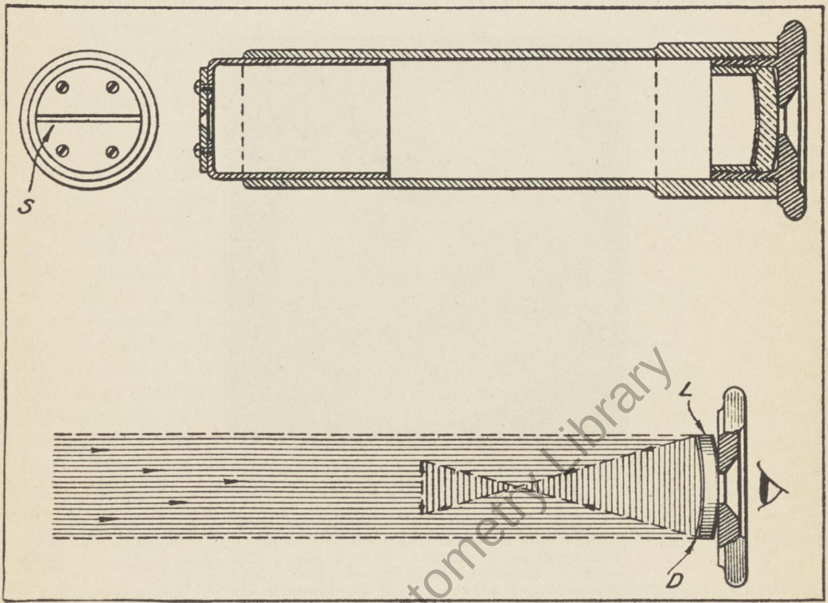


LUNAR PHOTOGRAPH TAKEN WITH A REFLECTOR

Made by Latimer J. Wilson with an 11-inch mirror and a Cramer contrast plate. Enlarged on a positive lantern plate, and contact negative made from that. The grain is due to the forced development to bring out the terminator. Wilson also uses Hammer press plates (ultra rapid—about 750—H. and D.) or special double coated Ortho plates.

Small Spectroscopes for use with telescopes are not highly satisfactory except when used with a fair-sized light gatherer—something larger than a 6-inch mirror, or even a 10-inch. They will show certain prominent lines in the spectra of first magnitude stars when the atmosphere is clear. In the *Scientific American,* December, 1926, Ernst Keil, maker of scientific instruments, briefly described a small spectroscope. His drawing, reproduced on page 260 virtually explains itself. *S* is the slit; *L* is the eyepiece lens, a common plano-convex spectacle lens rounded on an emery wheel and worked to focal length of about 3 inches; *D* is the transmission grating, a piece of transparent replica

from a diffraction grating (can be obtained from Central Scientific Supply Co.—Ed.). The replica is thin celluloid containing the grooves and is mounted on glass. Peel it off carefully and place it on the concave side of the lens. In *Popular Astronomy,* March, 1926, Jack Garrison described a small rig for solar spectroscopy. A. R. Dunlop states that he constructed for a few dollars a very efficient, simple spectroscope, using a replica grating, which gives fairly good views of solar prominences with a 2½-inch refractor. Carl Zeiss, Inc., sells a small spectroscope; also John Browning, Ltd.

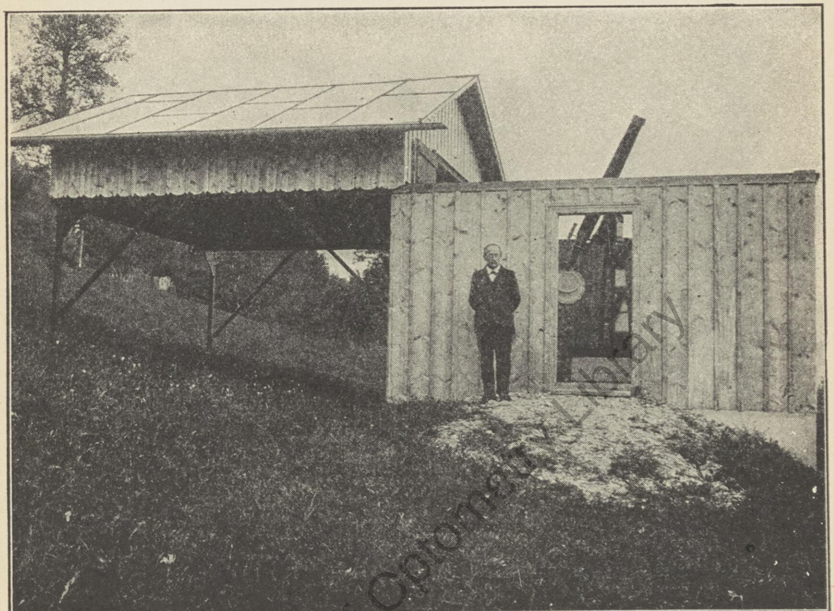


A SIMPLE, HOME MADE SPECTROSCOPE

Still another type is described in Barns' "1001 Celestial Wonders."

Observatories: Literature on observatories is scarce. See Bell, *The Telescope,* which describes several. In *Popular Astronomy,* May, 1922, J. Ernest G. Valden described an observatory for a 9½-inch reflector, with pyramidal revolving roof. He also described another small refractory in *Popular Astronomy,* October, 1920. William Braid White described a revolving dome (tin) observatory of small size, in *Popular Astronomy,* October, 1916. Charles Early described in *Popular Astronomy,* October, 1914, a tin-domed housetop observatory. A small, brick-walled observatory with dome was described in *Popular Astronomy,* issue for June-July, 1913. A small turret reflector of

unique design, combining in one structure the telescope mounting and observatory was described in *Popular Astronomy,* Aug.-Sept., 1927. In general, it is best to avoid complicated curved domes and stick to straight lines. One of the best of all types of "observatories" (actually it is only a housing) consists of an ordinary barn-like structure mounted on rollers on a track. During observation this "barn" is rolled away entirely, leaving the telescope in the open. Better yet, one may place the rollers and track at the plate level of the structure and merely slide aside the roof. These types require plenty of room.



A SIMPLE, STRAIGHT LINE OBSERVATORY

The roof rolls off the walls on tracks at the plate level. A little practical experience in building the conventional hemispherical dome for an observatory will speak loudly in favor of the straight line type which is free from the "fusswork" involved in fitting materials to curved surfaces.

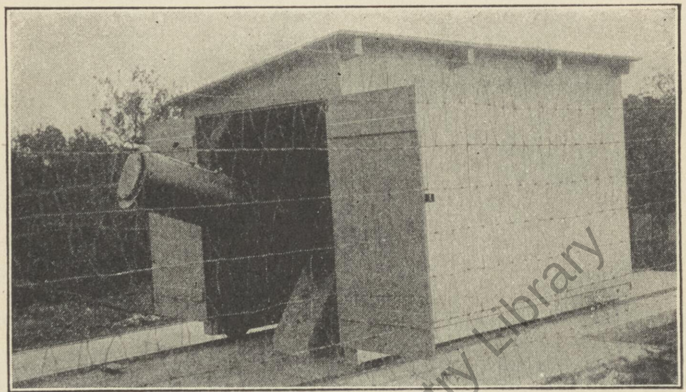
Back issues of *Popular Astronomy* can usually be purchased from that magazine. It is hoped that someone who is equipped to do fine work will some day construct the unique combined observatory and mounting proposed by Porter in an article in the May, 1921, issue of *Popular Astronomy.*

Pasadena Mounting: One of the most interesting reflecting telescopes thus

far completed as a result of the telescope campaign which the *Scientific American* has been conducting is that designed and built by F. M. Hicks.

The entire mounting was made by him, except the optical parts: the paraboloidal mirror has a diameter of $8\frac{1}{2}$ inches and a focal length of 5 feet. The outside tube is $10\frac{5}{8}$ inches in diameter. The 60-inch focal length is divided as follows: mirror to the $2\frac{3}{4}$-inch diagonal, $43\frac{1}{4}$ inches; diagonal to $1\frac{1}{2}$-inch prism, $10\frac{1}{2}$ inches; prism to eyepiece, $6\frac{1}{4}$ inches. This is Type A mounting.

In the polar axis was placed a Ford roller bearing hub which, with careful balancing of the tube, permits a delicate manipulation of the 90 pounds of tube and counterweight. Anyone who appreciates the convenience and comfort of a stationary eyepiece will never regret the extra work and expense required to build this "Pasadena type" of instrument.



A SIMPLE, PRACTICAL HOUSING

It is mounted on wheels or rollers running on a track at ground level. This is a 9-inch telescope made by Ritchey, for the Pasadena, California, High School. This photograph was furnished by the "Amateur Telescope Makers of Los Angeles."

The declination axis was constructed from a $2\frac{1}{2}$-inch "T" of cast iron, this being thick enough to permit boring out true and turning in the lathe where necessary. This is the main casting holding the prism and carries the cast iron cradle to which the large telescope tube is bolted.

The polar axis was constructed of two pieces of brass tubing brazed together at an angle suitable for the latitude where used. A Ford roller bearing hub, turned down to suit, was placed in the polar axis tube, where it provides the rotary motion of the polar axis.

Blueprint working drawings of *Pasadena Mounting,* Type A, may be obtained from F. M. Hicks for 35 cents.

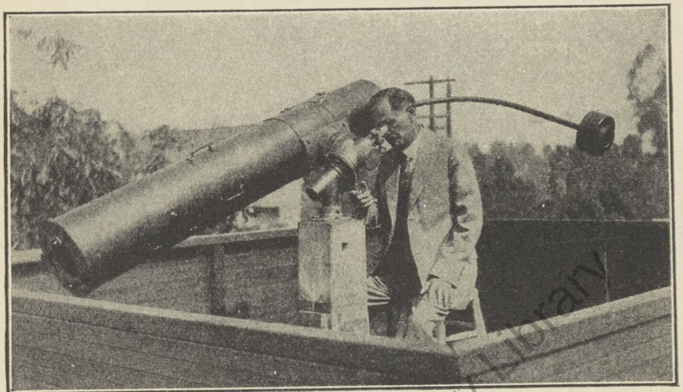
Three detailed working drawings are also available for a heavier "stationary eyepiece" mounting especially designed for schools and colleges, known as

"Pasadena Mounting Type B". These are sufficiently complete in detail to enable workers at a school or college having machine shop equipment to construct their own mounting. This construction is good for mirrors up to 12 inches in diameter. Cost one dollar postpaid.

Arrangements have also been made with a local machine shop (which is accustomed to do skilled work for a large observatory) to furnish rough or finished castings; or even the completed telescope, Types A and B.

Blueprints of a third mounting, made from a Studebaker drive shaft, and comparatively simple to build, may be had for 35 cents.

Setting Circles: Beginners often inquire whether it is worth while to equip a telescope with setting circles for finding a given star, from the *Ephemeris.*



F. M. HICKS AND THE PASADENA MOUNTING

Like its prototype the Springfield mounting, this makes use of two total reflection prisms, thus affording the luxury of a fixed, comfortable observing position. Blueprints may be had. This is Type A.

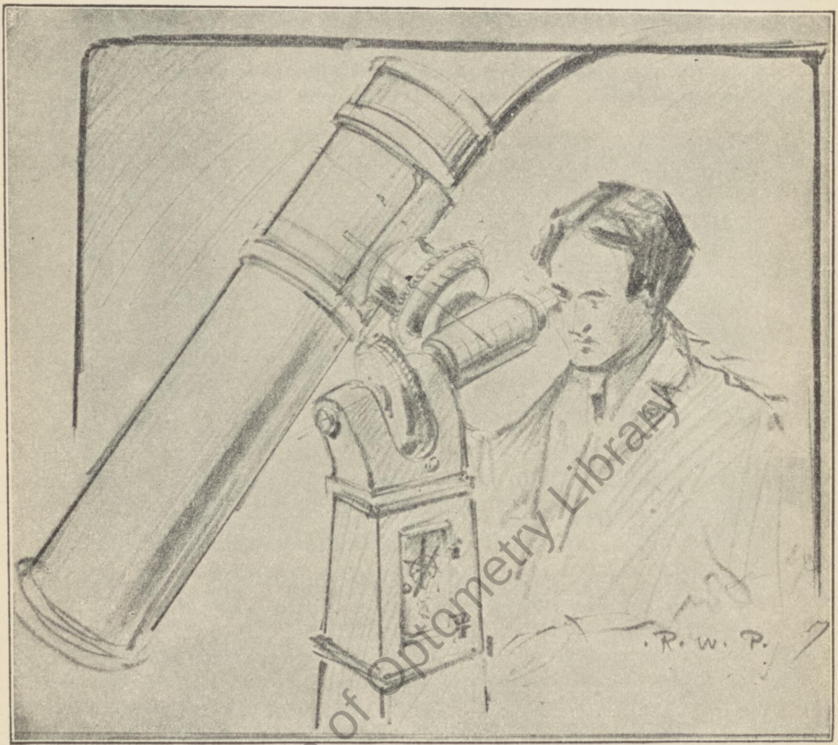
The following instructions set forth with exceptional lucidness the method by which the circles are used. They are the instructions prepared by Porter, for use with the "Garden Telescopes," of which he once made a hundred. Doing it, once one gets the "hang" of it by actual trial, is even simpler than reading about it.

"There are a great many interesting objects in the heavens that would be difficult to find unless we knew where to point the telescope. The Sun, Moon and nearer planets are obvious enough and are easily picked up by simply sighting upon them. But double stars, nebulae, star clusters, variable stars, must be located by means of the declination circle and the hour circle.

"The places of such heavenly bodies within the grasp of the garden telescope are fixed in the sky by declination (Decl.) and right ascensions (R.A.), very much as places on our Earth are fixed by latitudes and longitudes. So the first step is to set off the object's declination on the declination circle. The

other step is to lay off the right ascension on the hour circle, and to get this hour circle setting we must have a watch set to sidereal or star time.

"The watch, we will say, is running at first on Eastern (75th meridian) standard time. First, change it to local time by adding the time you are east of the 75th meridian, or subtracting if west. A person at Boston, for instance, sets his watch ahead about 16 minutes. A map of the United States will show



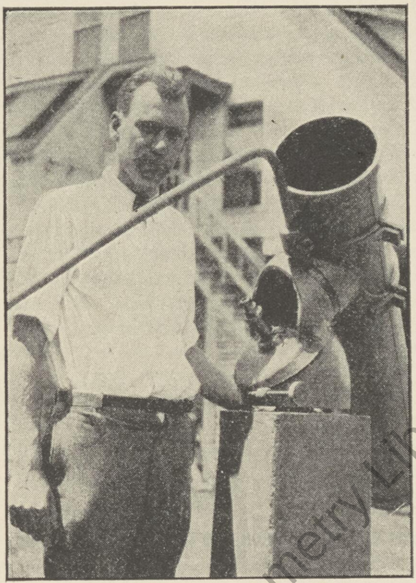
PASADENA MOUNTING, TYPE *B*

how many degrees and minutes of arc you are east or west of your standard meridian, and remember that there are 4 minutes of time for every degree of longitude. To the local time thus found add the proper interval from Table I. The result is star time.

"Sometimes this adds up more than 24 hours. If so, take 24 hours from it and use what is left. Even so, the time may be 18 or 21 o'clock, star time, or some such unfamiliar number; but don't let this disturb you. Star time

watches may be bought which actually have dials reading from 1 to 24 hours, but an ordinary watch face does just as well. If on adding the amount from the table it comes out over 12 hours—say, 18—take 12 from this and set the watch at 6 o'clock. Only remember it is really 18—6 plus 12. This is 'twenty-four hour time,' the same as used on many European railways.

"The watch is now keeping local star time. All this means is that any star



SPRINGFIELD MOUNTING, LARGE SIZE

Castings in iron or rustless duralumin are available for two sizes of the Springfield mounting. One is for a 6-inch mirror while the other, shown above, is for mirrors up to ten inches in diameter. The photograph shows Donald A. Patch, optical worker under Russell W. Porter, with the first large size Springfield mounting, which Patch made.

happening to be directly south, on your meridian, has the right ascension or position on the celestial hour circle shown on the dial of your watch. Stated another way, the watch shows the ascensions of all objects on your meridian at any time.

"And so, if you are after an object whose ascension is, say, 16 hours, and the watch dial reads 12 o'clock, the object will be found 4 hours east of you and you must lay off 4 hours on the hour circle (by moving the tube toward

the east) until the pointer is opposite the numeral IV, and with the declination setting already made the object will be seen in the eyepiece.

"To pick up, then, a celestial object with the telescope—first, set watch to local star time; second, set circle to declination of object; third, find the hour angle of the object and lay it off on the hour circle. To find the hour angle of the object, subtract the watch reading from the R.A. (increased by 24 hours if necessary). If this difference is less than 12 hours, lay it off on the hour circle by moving the blade into the east. If this difference is greater than 12 hours, subtract it from 24 hours and lay the difference off into the west.

"Fourth: Look into the eyepiece and see if the object is there—it may not be. I say may not, for it is easy at first to make mistakes somewhere in the computations. The best way is to take some familiar object like a first magnitude star visible at the time, and set the circles according to the directions given above. If you find the tube pointing off into another part of the sky you know some blunder his been made. Don't be alarmed. You may rest assured that that particular object is not 'off its course,' but will eventually be found plodding along in its accustomed place. Astronomers keep tabs on our celestial friends and they are always there—just as predicted.

"This method just described for finding an object in the heavens would not be called among astronomers a very precise one. It is not. But it is precise enough, for all we want is to direct the telescope so that the star, or nebula or cluster or whatever we are looking for, will be found in the field of view.

"An example: A possessor of a telescope living at Chicago wishes on the evening of August 5 to have a look at the great Andromeda Nebula. In the *Ephemeris* he finds:

The Great Nebula in Andromeda

Decl.	plus 40 degrees 46 minutes
R.A.	0 hours 38 minutes

"He first gets his watch running on local star time by the following computation:

Watch (90th Mer. Standard) reads	9.30 P.M.	
Watch slow on local time (see map)	7	
Local Sun time	9.37	
Table I for August 5	8.56	
Local Star time	17.93 or 18.33	
To set the watch, take away		12.00
Watch reading		6.33

"He therefore sets the watch to 6:33, remembering that the real time is always in this case 12 hours more, or 33 minutes past 18 o'clock.

"He is now ready with his watch and some sort of light—an electric torch is about the thing—to go out and set the telescope. The declination 40 degrees 46 minutes is first set off and the tube clamped. Since the object's R.A. is 0 hour 38 minutes, it is necessary to increase it by 24 hours in order to subtract the watch reading from it. This gives the object a R.A. of 24 hours

38 minutes. He then takes the difference between the object's R.A. and his watch reading and finds it to be:

R.A.	24.33
Watch	18.33
Diff.	6.05 east

and lays this off on the hour circle by moving the tube into the east. Of course, the watch hands have been moving all this time, and so has the Earth. The setting will thus really be made for the star time as given by the watch at the moment. This factor has not been taken into consideration in these examples. If all has gone well, he will see in the eyepiece a fuzzy-looking faint object greatly elongated, like a luminous lens seen on edge.

"Another example: This observer is at Los Angeles, California (Longitude 118 degrees W.). His watch is keeping Pacific (120 Mer.) time. It is therefore 2 degrees or 8 minutes slow on local time, and he moves the minute hand ahead 8 minutes. The time being Christmas Eve, he enters the table under that date and finds he must add 18 hours and 16 minutes to get star time. So he sets his watch ahead by that moment. This is how he figured it:

Watch (Pacific Time)	11.00 P.M.
Slow	.08
Table I..........................	18.16
	29.24

"We stated earlier that if the watch time figured up over 24 hours we would have to take 24 hours from it and use what was left, therefore

From	29.24
Subtract	24.00
	5.24

"So with his watch running on star time he goes into the garden. He desires to look at a star cluster. One is chosen at random from the lists given in some of the many handbooks.

Coarse cluster in Perseus, declination plus 42 degrees 21 minutes

R.A. 2 hours 36 minutes

"He sets the tube to the cluster's declination and clamps it. He then notes that the cluster's R.A. is less than star time and must therefore be increased by 24 hours, giving

R.A.	26.36
Watch	5.24
Hour Angle Diff.	21.12

"Consulting our rule he sees that when this difference is greater than 12 hours it must be subtracted from 24 hours and laid off in the west.

	23.60
	21.12
Hour Angle	2.48 West

and the Perseus Cluster is then on exhibition— a beautiful swarm of stars, condensed at the center, thinning out at the edge.

"This description of finding a celestial object does not take into account certain small corrections that may amount to as much as 4′ of arc. But if the eyepiece first used be a low-powered one, the field will take in about half a degree (30′) and the object will therefore be found somewhere near the center of the field. To the beginner the process will sound complicated, but after performing it a few times it will be seen that it is quite easy."

TABLE I

DAY OF THE MONTH

MONTH	1st		5th		10th		15th		20th		25th	
	H	M	H	M	H	M	H	M	H	M	H	M
January	18	41	18	56	19	16	19	36	19	56	20	15
February	20	43	20	59	21	19	21	38	21	58	22	18
March	22	37	22	53	23	13	23	33	23	52	0	12
April	0	40	0	55	1	15	1	35	1	54	2	14
May	2	38	2	54	3	13	3	33	3	53	4	12
June	4	40	4	56	5	16	5	35	5	55	6	15
July	6	38	6	54	7	14	7	34	7	53	8	13
August	8	41	8	56	9	16	9	36	9	55	10	15
Sept.	10	43	10	59	11	18	11	38	11	58	12	17
Oct.	12	41	12	57	13	17	13	36	13	56	14	16
Nov.	14	43	14	59	15	19	15	38	15	58	16	18
Dec.	16	42	16	57	17	17	17	37	17	56	18	16

Books on light, physics, etc.: The Editor is frequently asked to recommend a book on light. There are many, but rather than try to name them all a few are chosen with a view to their suitability. For the beginner: Sylvanus Thompson's *Light—Visible and Invisible.* This is a stenographic transcript of a series of popular lectures illustrated by means of apparatus, and the reader will feel that he is actually present at the lecture. *Physical Optics* by R. W. Wood, Professor of Experimental Physics at Johns Hopkins, is the last word on this subject, but it is primarily for advanced students who know higher mathematics. It is exhaustive (700 pages), but the larger part of it could be followed by the "graduate" from *Light—Visible and Invisible,* named above. It is interesting to note that Professor Wood is himself something of an "amateur" telescope maker and that he has followed with interest the recent popularization of the work; it was he who constructed the revolving dish of mercury telescope, mentioned elsewhere. Edser's *Light for Students,* might to good advantage form an intermediate course between the two books named above, for the ambitious home student. It is a 580 page work involving nothing worse than high school mathematics. Other books which fall outside this suggested course of study are *Light* by Prof. C. S. Hastings of Yale, an elementary treatise of great lucidity (out of print); *Light Waves and Their Uses,* by Prof. A. A. Michelson, also his *Studies in*

Optics (1927) ; *Physics of the Air,* by Prof. W. J. Humphreys, Chief Physicist of the U. S. Weather Bureau, which will explain many phenomena bearing indirectly on observation, seeing, atmospheric optics, etc., for the advanced amateur. In the latter connection, an article in *Popular Astronomy* for June, 1897, by Prof. A. E. Douglas, entitled *Atmosphere, Telescope and Observer,* will prove instructive concerning the causes of bad seeing.

To get a straight physics textbook treatment of light, Webster, Farwell and Drew's *General Physics for Colleges* is recommended. The book is unusually non-mathematical and is less "textbookish" than most texts, and more suitable for use where one cannot pursue the course in a regular class. Incidentally, it takes up the new physics of the atom; Einstein; space, time, gravitation; etc., and is the book The Editors of the *Scientific American* recommend to nearly all inquirers for a good physics text.

The Amateur's Telescope by Ellison is the original, published in England, from which Part II. of the present work was reprinted. It contains a few things not included in the present volume. A number of advanced amateurs have obtained it in order to have the original.

Bell—The Telescope: The average amateur will waste a lot of time and thought unless he possesses himself of a copy of Bell's invaluable 287-page work, *The Telescope.* Some of the many subjects treated are: early telescopes, optical glass and its working, testing glass; objective lenses; mountings, including several that are more or less unorthodox; eyepieces, their optical principles; binoculars; accessories such as star diagonals for easy zenith observing, polarizing eyepieces, ring and filar micrometers, clock drives, spectroscopes, diffraction gratings, the spectro-heliograph, photometers; the care and testing of telescopes, with various distorted star images and what they reveal about an objective lens under test; how to clean a dirty objective lens; lacquering mirrors; silvering; how to put a telescope into the meridian; housing and observations; resolving power, what it is, and why; and a brief course in microscopy. No "how-to-make-it" instructions are given, but the advanced amateur should not try to keep house without this book which fills in the whole general background on telescopes and their underlying principles.

German Telescope Books: For those who like to read German there is a little book entitled *Selbstherstellung eines Spiegel Teleskops,* by Prof. Dr. A. Miethe, published by Franckh'sche Verlagshandlung, Stuttgart, Germany, second edition 1921. *Das Moderne Spiegel Teleskop,* by Dr. Eugen von Krudy, has been recommended; The Editor has never seen it and does not know where it can be obtained.

Mirrors, Prisms and Lenses, by Southall, is a full, general treatise on applied optics and includes the theory of lenses, etc., but contains nothing on practical work. It is somewhat mathematical. A standard work.

The Adjustment and Testing of Telescope Objectives, by H. Dennis Taylor, of T. Cooke and Sons, Ltd., York, England, contains matter part of which is included in Bell's *The Telescope.* Taylor's book is not, however, specifically on *making* an objective.

Fath's *Elements of Astronomy* is a remarkably lucid textbook suitable for the beginner. It is not a large book—323 pages. The author has a knack of stating things in such a manner that one can get hold of them easily and carry away the main impression without becoming involved in the secondary details. At the other extreme in length is the new Russell, Dugan and Stewart *Astronomy,* in two volumes, 962 pages, "the most complete astronomy in the English language," yet not on this account abstruse or beyond the intelligent beginner's depth. Volume I, which may be purchased separately, treats of the astronomy of position and the solar system; Volume II treats the stars and embodies a 50-page treatise on astrophysics. Neither volume is mathematical, but parts of Volume II will require some knowledge of physics. Nevertheless, if The Editor were permitted to recommend but one book from the whole field of astronomy it would be this one. Although the volumes are splendidly produced the price is remarkably low. Intermediate in length between Fath's textbook and Russell, Dugan and Stewart's textbook is Prof. J. C. Duncan's *Astronomy.* This is a 380-page college textbook, mainly non-mathematical, and is very compact and full of information. It has been very favorably received by teachers of astronomy.

The Fundamentals of Astronomy, by Mitchell and Abbot, has been described as "a cross between a textbook and a popular treatise;" it is a textbook without the earmarks of a textbook—a sort of "tamed", humanized textbook.

Stetson's Manual of Laboratory Astronomy is used in first year college courses in astronomy, in connection with class work and actual observation. It outlines plenty of tasks for those who wish to knuckle down to systematic work.

Stetson's *Sky Map Construction for Everybody* is a 28-page booklet and is a reprint of parts of Stetson's *Manual of Laboratory Astronomy.* It will teach in a most practical way all the main constellations.

The New Heavens, by Dr. George Ellery Hale. Until about twenty years ago, astronomy was simply a more or less cut-and-dried member of the several sciences. Nearly all of the new birth of astronomy has had to do with the stars instead of the planets. Dr. Hale's book gives the reader a clear concept of what all this rebirth signifies, and gives it in popular language.

Todd's *New Astronomy* is particularly recommended, not to those who wish to study the newer developments of stellar astronomy and astrophysics but the ordinary astronomy of position, the movements of the heavenly bodies and similar astronomical commonplaces which usually baffle the beginner for some time. In making these things clear Todd's homely, detailed explanations are in a class by themselves. Some of the illustrations are somewhat old, but still they explain more clearly the points involved than any The Editor has seen, and where the amateur is forced to work alone instead of in a class room with other students and a teacher, this consideration always becomes important. He is likely then to discover himself hunting up his good, old-fashioned Todd, when after reading elsewhere the explanation of a given fact, he is still "as clear as mud" about it and is accusing himself of being "thick." It is no

secret, incidentally, that every beginner goes through a stage when all the motions of the heavenly bodies seem a hopeless tangle in his mind. Let him take hope; others have been there before him. Little by little the confusing points will clear up, as time goes on. To hasten the process, Todd's book is recommended.

Astrophysics: Within the past two years or more several leading books on astrophysics have been published. Dingle's *Astrophysics* has attracted widespread attention. *Stellar Atmospheres* is a notable astrophysical work by a well known Harvard astrophysicist, Dr. Cecelia H. Payne. *Astronomical Physics,* by F. J. M. Stratton, is a third. Finally, the second volume of Russell, Dugan and Stewart's *Astronomy* includes a sufficiently exhaustive treatment of astrophysics to suit the average advanced amateur.

Splendour of the Heavens: Next to Russell, Dugan and Stewart's *Astronomy,* we should chose, if we were in prison for life and were permitted but one work on astronomy, a large two-volume set of books entitled *The Splendour of the Heavens.* This is very comprehensive both in size (960 large pages, 524 illustrations) and scope (19 members of the *British Astronomical Association* treated their respective specialties in various chapters), and it even includes a detailed Moon map and star atlas. The publishers describe it as "a popular, authoritative astronomy." Alas—the book, though new (1925), is already out of print. It can, however, be consulted in the larger libraries.

Elements of Practical Astronomy, by Dr. W. W. Campbell. After the amateur has mastered descriptive astronomy, he may want to dip into celestial mechanics and see why the heavenly bodies act as they do. If he has had a previous speaking acquaintance with trigonometry, this standard textbook will be invaluable for this purpose. *Introduction to Celestial Mechanics,* by Moulton, resembles in scope the book last mentioned, except that it is more lengthy and more complete. It also requires previous work in higher mathematics.

Chauvenet's *Manual of Spherical and Practical Astronomy* is a two-volume work used by all astronomers. It is almost wholly mathematical. Volume I is devoted to the mathematics of astronomy, Volume II to applications of the same mathematics and descriptions of instruments. If you find the most hard-boiled textbooks becoming tame, and want something *solid* to chew on, Chauvenet is the very last word. It is a true *pièce de résistance.* It is not a new work, but that sort of thing never gets out of date, anyway.

American Ephemeris and Nautical Almanac. This old stand-by of the practical astronomer will become a necessity as soon as the amateur has mounted his telescope equatorially and put it into accurate adjustment with the earth's axis. From this time on, he can look up the desired star in the Ephemeris, set the circles on his telescope, look through the eyepiece, and the star is there! The Ephemeris gives the places (celestial longitudes and latitudes) of the Sun and planets for every day, the Moon for every hour and some 800 of the brighter stars; it also gives elements of all Moon-star occultations (stars eclipsed by the Moon), eclipses for the year, and those of the satellites of the planets—all published several years ahead. An abridged edition, plenty detailed enough for most of us, is also available.

Eclipses of the Sun, by Mitchell, is a standard work of large size. *Stars of the Southern Skies,* by Orr, will interest our Australian, South African, Argentinian and Chilean amateurs.

Starlight, by Director Shapley of Harvard Observatory, is an excellent, brief treatment of modern astronomical discoveries.

A Beginner's Star-Book, by Kelvin McKready, is well suited to the amateur, whether he has a telescope, opera glasses or eyes alone. Some chapters are: Learning to Observe; Star Maps for Any Year; Objects to be Seen; Catalog of Interesting Stars, etc. It contains a map of the Southern Skies. Pages, 150; large size.

Astronomy With an Opera Glass, by Garrett P. Serviss. A book which has stood the test of time. There are many books on this general aspect of astronomy. This is still one of the best.

The Friendly Stars, by Martha E. Martin. There is a steady demand for books that weave poetic feeling in with fact. Of this class of books, the above is a worthy representative. It is a naked eye star book.

Celestial Objects for Common Telescopes is a recent edition of a well-known work by Webb. There are two convenient sized volumes. The most useful feature is a rather detailed list of double stars and other showpieces of the heavens which an amateur whose telescope is equipped with adjusted setting circles will want to find. Goodacre's 22-inch Moon map is included.

A Guide to the Constellations, by Barton and Barton, will perhaps suit the average beginner better than any other atlas. Its maps are especially clear, in contradistinction to some maps which show so many things that the unaccustomed tyro is confused by them. The book is devoted exclusively to naked-eye, observational astronomy. One thing noted with gratitude is, that the pronunciation of each constellation and star is given, a boon to the isolated student. In addition to maps there is ample discussion of each heavenly feature.

Star Atlases: Upton's and Norton's star atlases are the two which are most used in schools. Norton's atlas was brought up to date in 1927 and in our opinion is the best available atlas for advanced amateur use. It is a large, thin volume with the emphasis on the contents rather than on physical appearance. The 17 large maps show 7,000 stars (six magnitudes) nebulæ, clusters, etc. The first half of the book is a sort of general compendium of practical star information and is as crammed full of facts as a Christmas pig. Ball's *Popular Guide to the Heavens,* an old standby which was brought up to date in 1926, is a thicker volume of smaller dimensions than Norton's and is notable as an example of fine book production. The thick chart paper and the 86 beautiful blue charts and illustrations make it a book to admire as well as use. *The Pathfinder Star Maps,* by Prof. Edward S. King, of Harvard, is a booklet containing charts similar to those published in the *Scientific American,* except a little larger and with explanation.

Moon Maps, Astronomical Pictures, etc.: No doubt more beginners become interested in the endless details of the Moon's surface than in any other object

of the heavens, and The Editor therefore receives frequent queries for Moon maps. An 18-inch map by Elger may be secured from the Eastern Science Supply Company, dealers in charts and other astronomical equipment, for two dollars. Goodacre's 24-inch Moon map forms a part of Webb's Celestial Objects for Common Telescopes, 6th Edition (described above). Walter Goodacre has also published a 60-inch map, both separately (out of print) and in the *Splendour of the Heavens.* H. P. Wilkens has made a 200-inch map, published in sections each measuring 22 x 30 inches. A photograph of a drawing of the Moon, 7 inches in diameter, by Porter, may be had from Yerkes Observatory; see also moonscape sketches in *Popular Astronomy,* October, 1916. A special collection of memoirs on the Moon may be purchased at very reasonable expense from the *British Astronomical Association;* send for list of published memoirs on Sun, Moon, planets, etc. Yerkes Observatory has for sale a large collection of astronomical photographs, lantern slides and transparencies. The prices put them within reach of most amateurs. Address the University of Chicago Press, Chicago, Ill. Photographic prints, especially of the Moon, may also be purchased from the Mt. Wilson Observatory, Pasadena, Calif. Unmounted prints cost about fifty cents apiece, most of them are extremely beautiful and are fit for framing. There is a very good 24-inch Moon map drawn by Karl Andel and reproduced by V. Neubert and Synové, Prague XVI, Czecho-Slovakia. It shows all the formations under rising Sun illumination.

1001 Celestial Wonders is a new book by the amateur telescope maker Charles Edward Barns. This is the best book we know for the amateur whose telescope is equipped with setting circles, because he can make with it a systematic canvass of the heavens, since each chart blocks off a small area and the text opposite tells what to look for in it. Pocket size. Part II is on instrument making, including reflector and refractor, eyepieces and small spectroscopes.

A Photographic Atlas of Selected Regions of the Milky Way is unique; its charts are *actual photographs,* 51 of them, each 9 inches square, taken with the Bruce Photographic Telescope by the late venerated Professor Barnard. This two volume set is most suitable for the amateur who wishes to make a detailed study of the peculiarities of the Galaxy, rather than as a star atlas. Each photograph is explained in detail. A beautiful work.

Other Literature. Draper's original paper on "The Construction of a Silvered Glass Telescope, Fifteen and a Half Inches in Aperture," and Ritchey's paper, "On the Modern Reflecting Telescope and the Making and Testing of Optical Mirrors," appeared in the *Smithsonian Contributions to Knowledge,* Volume 34, 1904. This volume is out of print but may be consulted in some libraries. Both papers were reprinted in the *Scientific American Supplements,* the Ritchey paper appearing first (December 24 and 31, 1904 and January 7, 14 and 21, 1905), and the Draper paper July 29 and August 5, 12 and 19, 1905. These Supplements are not available except in some public libraries. The Rev. C. D. P. Davies published an article on the testing of

paraboloidal mirrors, in *Monthly Notices of the Royal Astronomical Society,* March, 1909; "The Poor Man's Telescope" (*i.e.,* the reflector) by R. W. Porter was published in *Popular Astronomy,* November, 1921 (out of print); also see "Knife-Edge Shadows" by the same author, *Astrophysical Journal,* June, 1918 (out of print). "The Polar Reflecting Telescope" by R. W. Porter appeared in *Popular Astronomy,* May, 1916. "The Enclosed Observing Room," by the same author, was published in *Popular Astronomy,* May, 1917, and reprinted in *Scientific American Supplement 2170,* which is not, by the way, obtainable from the *Scientific American;* try the H. W. Wilson Company, dealers in old issues, who still have certain of the Supplements left in stock.

Astronomical Societies: As an added incentive to persistence on the part of the new worker to hang on when things are going wrong and when there is perhaps an inclination to chuck over the whole job, there are two interesting scientific societies into which almost any amateur with serious intentions and a telescope is welcomed; the *American Association of Variable Star Observers* (A. A. V. S. O.) and the *American Meteor Society.* With regard to the former the situation is this: professional astronomers would like to keep close watch of a large number of stars which vary in brightness over certain periods of time. To perform this work for science there are not, however, enough professionals to go around. The A. A. V. S. O. was therefore organized with a large share of its membership among amateurs, and its sponsors state that the association stands ready to help new workers with charts, blanks and instructions. Annual membership is two dollars. At present something under 100 active observers carry on the work and their reports are regularly published in *Popular Astronomy.*

The other organization, the *American Meteor Society,* welcomes to membership all persons who are interested in astronomy. Personal application should be made. (See directory.) Dues are one dollar. All who are using moderate sized telescopes are urged to keep a record of telescopic meteors seen by them in the course of their observation. Blanks and instructions will be sent free on application, and without obligation to join unless one wants to. Members also secure and transmit data on large fire balls, photograph meteors, etc.

The Editor often receives inquiries whether there are any general astronomical societies open to the amateur. There are several, and while they reserve the privilege of rejecting application for membership it is seldom necessary to exercise it. In most of them the amateur is made altogether welcome even if he does not yet possess much knowledge of astronomy. Among the professional personnel of astronomy there is no tendency toward loftiness or exaltation, and virtually all professionals are genuinely interested in the efforts of amateurs to break into the game; they are only too anxious, in fact, to see a more widespread interest aroused in their science and generally they willingly facilitate the admission of amateur enthusiasts to all but the purely professional associations.

The *American Astronomical Society* is frankly for professionals (though most of its members also belong to several societies made up largely of amateurs). It publishes no journal but meets twice a year in various parts of

the country and the meetings, which are not large, are generally open to serious amateurs. Naturally, the subjects discussed are not elementary.

The *Royal Astronomical Society,* Burlington House, London, W. 1, England, is for professionals and advanced amateurs. There is a two guinea initiation fee and the annual dues are two guineas. A substantial publication, the *Monthly Notices,* is included. This is rather an abstruse journal. Candidates must be recommended by three members (among the members are most American professionals).

The *Royal Astronomical Society of Canada* is open to all (not necessarily Canadians) who are interested in astronomy and its *Journal* states that "more members are desired." At present there are over 600 members. Annual fee, two dollars, which includes subscription to the *Journal* (see page 276); also the invaluable Observer's Handbook for the current year. (See directory.)

The *British Astronomical Association* is "open to all persons interested in astronomy," but requires that candidates be proposed either by one member or by two persons of weight and standing and from personal knowledge. Entrance fee, five shillings; annual subscription to the *Journal* (monthly) one guinea. The annual Handbook for observers is included. (See directory.)

The *Astronomical Society of the Pacific* is "open to all who feel an interest in the subject of astronomy." Annual dues, five dollars; no initiation fees. The interesting periodical is called the *Publications* (see page 276) and subscription is included in the dues. While this is an amateur society, as a matter of fact most of the noted professionals on the Pacific Coast are also members because they are interested in the amateur's endeavors. This makes for close liaison between the two groups, which tend to shade more or less into one another. The membership is large and is by no means confined to the west. (See directory.)

The *Amateur Astronomer's Association,* organized 1927, is for amateurs and is at present confined to New York, though several cities in other states are planning to organize local branches as has been done in Canada by the R. A. S. C. Membership, two dollars a year; no initiation fee. No publication at present time (1928).

The *Société Astronomique de France* has more than 5,000 members in all parts of the world and is mainly composed of amateurs. Foreign membership is 30 francs a year and the publication, *L'Astronomie* (see page 276) is included. For a comparatively small sum at the present exchange rate, one may also become a founding or life member. This would be an interesting way to keep up one's French throughout life; astronomical French is easy, due to the virtual identity of the scientific words. The publication is most attractively produced and illustrated. Address Secrétaire Général and enclose an international reply coupon, obtainable for five cents at any P. O. (See directory.)

Optical Journals: The Journal of the Optical Society of America and Review of Scientific Instruments is a rather advanced monthly scientific journal which those who have access to large libraries will do well to investigate. Subscription, five dollars a year. This journal is sometimes confused with the

Journal of Scientific Instruments, published monthly by the Institute of Physics with the cooperation of the National Physical Laboratory, England, 30 shillings a year. This journal is devoted to workers in every branch of science and mechanics involving the necessity for accurate measurements. The more advanced amateurs who enjoy higher mathematics and physical optics will possibly get an occasional sidelight from these journals, which are kept on file at university libraries, etc.

PERIODICALS ON ASTRONOMY

Popular Astronomy, Northfield, Minnesota. The best known of the purely astronomical journals. Contains a mixture of elementary with advanced articles, and is always interesting. (Ten numbers a year, $4.00 (foreign, $4.50).

Publications of the Astronomical Society of the Pacific. Perhaps a little more advanced than the above, yet full of interest. Six numbers a year, $5.00.

Astrophysical Journal. Monthly. Covers spectroscopy and astrophysics. Advanced. University of Chicago Press, Chicago, Ill. In United States and possessions, $6.00 a year.

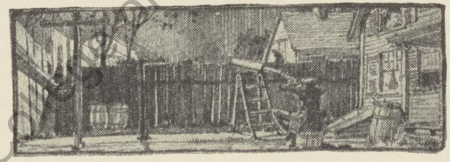
The Monthly Evening Sky Map, 367 Fulton St., Brooklyn, N. Y. Contains practical constellation and planet finder map arranged for the current month; also items of popular interest to amateurs. Monthly. $1.50 per year.

Journal of the Royal Astronomical Society of Canada. (See pp. 275, Societies.)

The Observatory, Royal Observatory of Greenwich, London, S.E. 10, England. Twenty shillings a year. Monthly.

English and Amateur Mechanics, 2 Breams Buildings, Chancery Lane, London, E.C. 4, England. Occasionally publishes letters from amateur astronomers and telescope makers. Weekly. Seventeen shillings a year. (Formerly *English Mechanics.*)

L'Astronomie is much like *Popular Astronomy,* but is published in the French language. (See pp. 275, Societies.)



DIRECTORY

To facilitate ready access to institutions and individuals mentioned in the text, and to promote direct intercourse between amateurs, many of the addresses are here placed before the reader. It must be remembered that as time elapses some of these addresses will become obsolete.

Amateur Astronomer's Association, American Museum of Natural History, 77th Street and Central Park West, New York.
American Association of Variable Star Observers, Leon Campbell, Harvard College Observatory, Cambridge, Mass.
American Meteor Society, Care of Professor Charles P. Olivier, Director Flower Observatory, University of Pennsylvania, Philadelphia, Pa.
Amateur Telescope Makers of Los Angeles, John Gayton, president, 1041 Chadwick Drive, Los Angeles, Calif.
American Optical Co., Southbridge, Mass.
Anderson, Dr. J. A., Mt. Wilson Observatory, Pasadena, Calif.
L'Astronomie (see Société Astronomique de France).
Astronomical Society of the Pacific, C. H. Adams, secretary, 803 Merchant's Exchange Bldg., San Francisco, Calif.
Astrophysical Journal, 5750 Ellis Ave., Chicago, Ill.
Bakelite Corp., 247 Park Ave., New York.
Bausch and Lomb Optical Co., Rochester, N. Y.
Beck, R. and J., Ltd., 68 Cornhill, London, E.C. 4, England.
Besley & Co. Chas. H., 118 North Clinton St., Chicago, Ill.
Binney and Smith, 41 East 42nd St., New York.
Boston Gear Works, Norfolk Downs, Mass.
Boutell, Hugh G., U. S. Bureau of Standards, Washington, D. C.
British Astronomical Association, 8 Maze Hill, Greenwich Park, London, S.E. 10, England.
Brookings, Ernest, Care of Jones and Lamson Machine Co., Springfield, Vt.
Browning, Ltd., John, 138 Strand, W.C. 2, London, England.
Bureau of Standards, U. S., Washington, D. C.
Carborundum Company, Niagara Falls, N. Y.
Central Scientific Supply Co., 460 East Ohio St., Chicago, Ill.
Chance Brothers, Birmingham, England. (See Sharp, Donald.)
Cooke, T. and Sons, Ltd., York, England.
Cooper, Charles and Co., 4 Mulberry St., New York.
Corning Glass Works, Corning, N. Y.
Crucible Steel Co. of America, 17 East 42nd St., New York.
Curtis, Dr. Heber D., Director Allegheny Observatory, Pittsburgh, Pa.
Cutler, Rev. Harold N., 91 Ilford Ave., North Arlington, N. J.
Dadant and Sons, Hamilton, Ill.
Darling, Stephen F., 13 Chauncey St., Cambridge, Mass.
Douglas, Professor A. E., University of Arizona, Tucson, Ariz.
Dunlop, A. R., Box 745, New Westminster, B. C., Canada.
Eastern Science Supply Co., Box 1414, Boston, Mass.
Egyptian Lacquer Mfg. Co., 90 West St., New York.

Ellison, Rev. W. F. A., Director Armagh Observatory, Armagh, Northern Ireland.

Ellms, Robert, Baldwin-Wallace College, Berea, Ohio.

English Mechanics (now English and Amateur Mechanics) 2 Bream's Buildings, Chancery Lane, London, E.C. 4, England.

Everest, A. W., General Electric Co., Pittsfield, Mass.

Fecker, J. W., 1954 Perrysville Ave., Pittsburgh, Pa.

Gaertner Scientific Corp., 1201 Wrightwood Ave., Chicago, Ill.

Garrison, Jack, 802 Hamilton Ave., Indianapolis, Ind.

General Electric Co., Att: Mr. W. H. Jones, 1 River Road, Schenectady, N. Y.

General Electric Review, Schenectady, N. Y.

Glass Industry, 50 Church Street, New York.

Goodacre, Walter, Warratah 125, Holden Road, Worth Finchley, London, N. 12, England.

Hamilton Emery & Corundum Co., 30 Church St., New York.

Hamilton, Professor George H., "Iona", Mandeville, Jamaica, B.W.I.

Hargreaves, F. J., Mirastelle, Woodland Way, Kingswood, Surrey, England.

Hastings, Professor Charles S., Yale University, New Haven, Conn.

Haynes Stellite Co., Kokomo, Ind.

Hicks, F. M., 1315 South Oakland Ave., Pasadena, Calif.

Hilger, Adam, Ltd., 24 Rochester Place, Camden Road, London, N.W. 1, England.

Holcomb Steel Co., 1 Dominick Street, New York.

Hubert Optical Abrasive Co., Tilton, N. H.

Ingalls, Albert G., Telescope Editor, the Scientific American, 24 West 40th St., New York.

Ions, Clarendon, 513 Realty Board Bldg., Miami, Florida.

Journal of the Franklin Institute, 15 South Seventh St., Philadelphia, Pa.

Journal Opt. Soc. of Am. and Rev. of Sci. Inst., Menasha, Wisc.

Journal of Scientific Instruments, Cambridge University Press, Fetter Lane, London, E.C. 4, England.

Journal of the Society of Glass Technology, Sheffield, England.

Keil, Ernst, 105 S. Catalina Ave., Pasadena, Calif.

King, Prof. Edward Skinner, Harvard College Observatory, Cambridge, Mass.

Lee, John C., Grove St., Wellesley, Mass.

Lower, Harold A., 1032 Pennsylvania St., San Diego, Calif.

Lutz, G. L., Good Roads Equipment Corp., City Center Bldg., Philadelphia, Pa.

Mason, Henry H., East Pensacola, Fla.

Monthly Evening Sky Map, 367 Fulton St., Brooklyn, N. Y.

Mt. Wilson Observatory, Pasadena, Calif.

Munning, A. P. and Co., Matawan, N. J.

Nakamura, Dr. Vi, Kyoto Imperial University, Kyoto, Japan.

National Physical Laboratory, Teddington, Middlesex, England.

Nature, Macmillan & Co., Ltd., St. Martin's St., London, W.C. 2, England.

Noblitt, Loren S., Alma College, Alma, Mich.

Optical Society, 1 Lowther Gardens, Exhibition Road, South Kensington, London, S.W. 7, England.

Ottway & Co. Ltd. W., Ealing, London, W. 5, England.
Patterson Brothers, 27 Park Row, New York.
Pease, Dr. F. G., Mt. Wilson Observatory, Pasadena, Calif.
Pierce, John M., 11 Harvard St., Springfield, Vt.
Pittsburgh Crushed Steel Co., A. V. R. R. and 61 St., Pittsburgh, Pa.
Popular Astronomy, Carlton College, Northfield, Minn.
Porter, Russell W., Optical Associate, Jones and Lamson Machine Co., Springfield, Vt.
Radium Luminous Material Corp., 58 Pine St., New York.
Ritchey, Professor G. W., l'Observatoire de Paris, 61 Avenue de l'Observatoire, Paris, (14e), France.
Rogers, H. L., 10 Adelaide St. East, Toronto, Ont., Canada.
Root, A. I., Co., Medina, Ohio.
Royal Astronomical Society, Burlington House, London, W. 1, England.
Royal Astronomical Society of Canada, 198 College St. Toronto, Ontario, Canada.
Royal Observatory of Greenwich, London, S. E. 10, England.
Saint-Gobain, Chauney et Cirey, 1 bis, Place des Suassaies, Paris (VIIIe), France.
Scientific American, 24 West 40th Street, New York.
Sellers, F. J., 42 Church Crescent, London, N. 10, England.
Shapley, Prof. Harlow, Harvard College Observatory, Cambridge, Mass.
Sharp, Donald, agent for Chance Brothers, Hamburg, N. Y.
Simonds Saw & Steel Co., Lockport, N. Y.
Société Astronomique de France, Madame Camille Flammarion, Secrétaire Général, Observatoire de Juvisy, Seine-et-Oise, France.
Spencer Lens Co., Buffalo, N. Y.
St. Clair, B. W., Director Standardizing Laboratory, General Electric Co., West Lynn, Mass.
Telescope Makers of Springfield, Oscar Marshall, Secretary, 135 Wall Street, Springfield, Vt.
Thomson, Professor Elihu, Director Thomson Research Laboratory, Lynn, Mass.
Vapo-Cresoline Co., 62 Cortlandt St., New York.
Wadsworth, Professor F. L. O., Box 268 E. Liberty Station, Pittsburgh, Pa.
Wallace, Vard B., 66½ Ontario Ave., Long Beach, Calif.
Ward's Natural Science Establishment, Rochester, N. Y.
White, William Braid, 5149 Agatite Ave., Chicago, Ill.
Wilkins, H. P., in care of English and Amateur Mechanics.
Wilson, H. W., Co., 958 University Ave., New York.
Wilson, Latimer, 1405 Gartland Ave., Nashville, Tenn.
Wood, Dr. R. W., Johns Hopkins University, Baltimore, Md.
Woodside, Charles L., 40 Broad St., Boston, Mass.
Wright, Dr. F. E., Geophysical Laboratory, Washington, D. C.
Yalden, J. Ernest G., 120 Woodridge Place, Leonia, N. J.
Yerkes Observatory, Williams Bay, Wisc.
Zeiss, Carl, Inc., 485 Fifth Avenue, New York, (Jena, Germany).

MATERIALS

No pretense is made that the following list is complete. Most of the sources listed are those previously tried by The Editor, or known to him through other amateurs. The addresses of the firms named may be found in the Directory, pages 277 to 279.

Bakelite Cement: Bakelite Corp.
Brass Tubing: Patterson Bros.; Besley and Co.
Carborundum: The Carborundum Co.
Chance Brothers Optical Glass: Donald Sharp, American Agent.
Crushed Steel: Pittsburgh Crushed Steel Co.
Eyepieces, prisms, etc.: Spencer Lens Co.
Emery: Hamilton Emery and Corundum Co., 1 pound can, 6 F, Turkish emery, 50 cents postpaid.
Finders: Gaertner Scientific Corporation.
Garbite: Hubert Optical Co.
Hastings, 3 lens eyepieces: John M. Pierce; J. W. Fecker.
H C F: Root, A. I. Co.; Dadant and Sons.
Invar: Crucible Steel Co. of America; Holcomb Steel Co.; Simonds Saw and Steel Co.
Lacquer: Egyptian Lacquer Mfg. Co.
Lamp, small, for Knife-edge Test: Vapo-Cresoline Co. (40 cents, postpaid).
Magnetic black rouge: Binney & Smith.
Pyrex: Corning Glass Works.
Rouge: A. P. Munning & Co. (Best grade, optician's lump rouge).
Quartz, fused: General Elec. Co., Schenectady Works.
Radium paint: Radium Luminous Corp.
Replica Gratings: Central Scientific Supply Co.
Sira Abrasive: R. & J. Beck, Ltd.
Spectroscopes: Carl Zeiss, Inc.: John Browning, Ltd.
Stainless Steel mirrors: Ottway & Co., Ltd.
Stellite: Haynes Stellite Co.

General Supplies for Amateurs: With a view to enabling the worker to obtain supplies of the exact and somewhat peculiar kind required, it was soon found necessary to prevail upon some amateur, who would, of course, understand these requirements *from his own actual experience* in amateur telescope making, to become a sort of central distributor of them. John M. Pierce of Springfield, Vermont, author of Part VII, was chosen. Pierce is Director of Vocational Education in the High School at Springfield. When chosen he had already made a number of telescopes for his own use, and he is an active member of the "Telescope Makers of Springfield", of which body of amateurs R. W. Porter, author of Part I, is the president. In the cellar workshop in his home Pierce assembles and forwards to the most distant amateurs virtually every sort of optical supplies. To the beginner, especially, it is distinctly convenient to be able thus to obtain in one package the necessary outfit—plate glass disks, pitch, abrasives and rouge—apportioned in the proper quantities to enable him to commence work at once.

BOOK LIST

The following is a selected list of books described in the present volume. These (or any other books) may be obtained from the *Scientific American*, 24 West 40th Street, New York. The prices quoted *include postage in the United States and Territories.* For foreign orders add 10 cents per book to the prices given, for registration. Books are not sent on approval.

Ball: Popular Guide to the Heavens	$ 7.70
Bell: The Telescope	3.15
Barnard: Atlas of Selected Regions of the Milky Way	10.20
Barns: 1001 Celestial Wonders	2.50
Barton and Barton: Guide to the Constellations	2.65
Campbell: Elements of Practical Astronomy	2.90
Chauvenet: Manual Sph. and Pract. Astron. (2 volumes)	10.20
Dingle: Astrophysics	8.70
Duncan: Astronomy	3.90
Edser: Light for Students	2.50
Ellison: The Amateurs' Telescope	2.15
Ephemeris and Nautical Almanac	1.00
Fath: Elements of Astronomy	3.15
Hale: The New Heavens	1.65
Hodkin and Cousen: Textbook of Glass Technology	12.00
King: Pathfinder Star Maps	1.40
Martin: Friendly Stars	2.15
McKready: Beginner's Star Book	5.20
Michelson: Studies in Optics	2.15
Mitchell: Eclipses of the Sun	5.20
Mitchell and Abbott: Fundamentals of Astronomy	3.15
Moulton: Introduction to Celestial Mechanics	4.15
Norton: Star Atlas	3.90
Olivier: Meteors	6.20
Orr: Stars of the Southern Skies	1.40
Payne: Stellar Atmospheres	2.65
Russell, Dugan, Stewart: Astronomy (2 volumes)	5.30
Serviss: Astronomy with an Opera Glass	3.15
Shapley: Starlight	1.15
Southall: Mirrors, Prisms and Lenses	4.65
Stetson: Manual of Laboratory Astronomy	2.10
Stetson: Sky Map Construction for Everybody	.50
Stratton: Astronomical Physics	5.20
Thompson: Light—Visible and Invisible	2.90
Todd: New Astronomy	1.95
Upton: Star Atlas	3.15
Waters: Astronomical Photography	2.00
Webb: Celestial Objects for Common Telescopes (2 volumes)	6.70
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(A systematic study of the book by subjects, using the index, is recommended.—The Editor.)